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New Measurements of the
Fluorescence Efficiency of Air
Under Electron Bombardment

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LOS ALAMOS • NEW MEXICO

Report written: August 1967

Report distributed: January 17, 1968

New Measurements of the
Fluorescence Efficiency of Air
Under Electron Bombardment*

by

Paul L. Hartman

*Work done under the auspices of the AEC partially in response to ARPA Work Order No. 631, Program Code No. 5820.

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NEW MEASUREMENTS OF THE FLUORESCENCE EFFICIENCY OF AIR
UNDER ELECTRON BOMBARDMENT

by

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ABSTRACT

The fluorescence efficiency of air under electron bombardment has been measured at a pressure corresponding to an altitude of 65 km, for electron energies near 700 eV, with the principal measurements at the bright 3914-Å band of the N_2^+ ion. Efficiencies for the 3914-Å band from two methods of observation were in good agreement, and gave a value $\eta_{3914} = 0.34\%$. Spectra were obtained for air emission in the range 2500 to 12,000 Å. Comparison of the radiation in the 3914-Å band to that in the whole spectrum gave a total efficiency of $\eta_{total} = 1.86\%$ for this spectral range. Efficiencies of some individual bands of the N_2 first and second positive systems were also determined by comparison with the 3914-Å band.

The 3914-Å efficiency, for electron energies of 165 eV to 1 keV, was found to be nearly independent of energy, rising perhaps as the 0.07th power of the energy in this range.

The dependence on pressure of the light output in the spectral range 3000 to 11,000 Å was observed for electron energies of 750 and 1425 eV and pressures of 30 to 960 μ . The efficiency of the 3914-Å band is independent of pressure below 100 μ . Above 100 μ , efficiencies of the N_2^+ first negative and N_2 first and second positive bands decrease with increasing pressure, the first positive decreasing most rapidly and the second positive least rapidly. Intensities of some N_2^+ Meinel bands were compared with the first positive (0,0) band at pressures of 1 to 50 μ in nitrogen and air. The intensity of the Meinel bands relative to the first positive band increases by an order of magnitude in going from nitrogen pressures of 50 to 1 μ .

As a check on the photometric techniques, the cross section for excitation of the 3914-Å band by 750-eV electrons was measured and found to be in good agreement with results obtained by Holland.⁹ Some electron range measurements also gave results in agreement with previous work.

INTRODUCTION

During 1960 and 61, the writer was privileged to spend a year at the Los Alamos Scientific Laboratory, at which time he obtained some preliminary results on the fluorescence efficiency of air under electron bombardment. A meeting paper was presented on the work,¹ and a LA..MS report was written,² but no further publication was made. The work was to be continued, but circumstances prevented this. With another sabbatical year available during 1966 and 67, it seemed appropriate to return to Los Alamos and attempt to bring the work to some satisfactory conclusion. This report summarizes the year's work and presents the results obtained on the efficiency and other related matters.

RESUME OF THE 1960-1 RESULTS

The preliminary efficiency results were obtained in three ways. Each method involved firing an electron beam of known current and energy into a sizable volume of air so that all the beam energy was expended in the gas. An integration then determined the total light output. Determining the beam characteristics is a problem in physical electronics, and integrating the light to determine to what power it corresponds is a problem in photometry. The three methods differed principally in the way in which the light was integrated.

The first method made use of an optical integrating sphere enclosed in a large vacuum chamber. The electron beam was injected through a port in the sphere, and the energy was deposited in air within it. Photometric measurements were made at a window looking in to the white interior surface of the sphere.

In the second method, the electron beam was fired into the same vacuum chamber without the large integrating sphere. A small integrating sphere and photodetector were swung around the periphery of the glow so that the open port of the sphere, facing the glow, moved along a meridian circle with the beam direction as axis. Sampling each zone of latitude in this manner allowed a determination of the total amount of light leaving the glow.

Finally, a third method, which evolved in preliminary studies, used a cylindrical glass bell jar.

The beam was injected into the bell jar, and the photometric detector placed at a great enough distance that one might treat the glow as a point source. The geometry of the setup determined the fraction of the light received by the detector, and thus one could derive the total. So the bell jar, besides serving its original purpose as a means of studying the characteristics of some of the problems in the work, also offered an attractive alternative method for the specific efficiency measurement.

The photometry in all three cases was done with unfiltered photomultipliers. Their response as a function of wavelength was determined by exposure to radiation of various wavelengths whose intensity was determined with a thermopile. When the detector was exposed to the glow, one had to determine what fraction of the photocurrent came from the various spectral features in the light. This was done by making spectral scans of a glow produced in the bell jar. The detector looked at the bright part of the glow, at close range, through a monochromator whose transmission was separately determined. These operations permitted determination of the efficiency at any spectral feature included in the range of the detectors.

Determining the input beam characteristics was not easy, particularly for the optical integrating sphere, with its insulating surface. Both for the sphere and to some extent for the bell jar, problems were encountered in the input current measurement. To alleviate the difficulty, a positive bias of 22 V was applied between the sphere and the gun injection tip to prevent slow electrons from escaping to the gun tip. This will be discussed later.

The values found for the fluorescence efficiency of the 3914-Å N_2^+ first negative band in air were as follows:

Method	η_{3914}
Bell jar	0.26%
Integrating sphere	0.29%
Scanning detector	0.43%

for an average of 0.33%. A total efficiency for the spectral region from 3000 to 11,000 Å was about 1.8%.

The 3914-Å band average value was higher than that obtained from simple calculations³ using

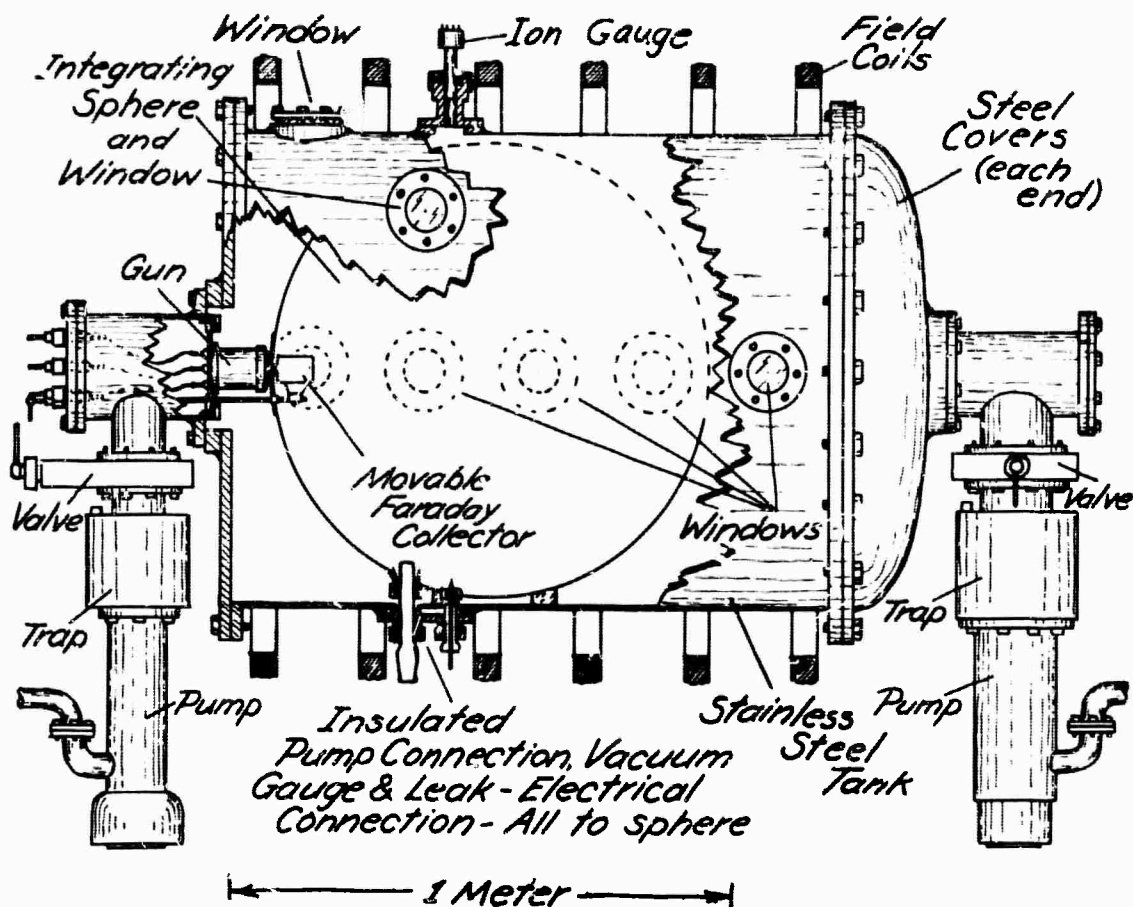


Fig. 1. Essentials of the large vacuum system and integrating sphere.

published electron excitation cross sections.⁴ A calculation based on more recent cross-section measurements⁵ yields a still higher efficiency, but the inference of better agreement between the efficiency and cross-section measurements has been criticized⁶ as unwarranted. Because of these unresolved questions and the preliminary nature of the results, it seemed appropriate to arrive at a reliable value, making the best corrections that one could.

THE NEW MEASUREMENTS --- 1966-7

We decided not to use the scanning detector in making the new measurements; it was slow and awkward and gave a higher value than the other methods. The other two methods would be used, with emphasis on the optical integrating sphere.

APPARATUS

The large vacuum system enclosing the integrat-

ing sphere is the one used before, fitted with new pumps, traps, and valves. It is shown diagrammatically in Fig. 1, taken from the earlier report. The sphere is of spun aluminum, $\frac{5}{4}$ in. in diameter, and fits closely in the enclosing vacuum chamber. A well-perforated alignment sleeve between the gun and the sphere provides a stage of differential pumping. An insulated, blackened tube, vacuum-sealed to the sphere and outer window, prevented pumping through the observation port. Insulating fittings, also vacuum-sealed at the sphere and outer wall, allow for gas leak, pressure measurement, and pump connections into the sphere. A single metallic connection at the same location permits measurement of the net current into the sphere. Windows along the sides of the vacuum chamber allow measurements and observation from the outside when the sphere is removed. Coils spaced between these windows allow a magnetic field of up to 100 gauss to be imposed on the glow.

New instrumentation included a reliable pressure gauge (a continuously recording capacitance manometer); a reproducible commercial vacuum leak; a dc electrometer amplifier to read phototube currents; provision for chopping the electron beam in some applications; and a synchronous detector for low signal measurement in the presence of noise in these same applications.

Four different types of photomultipliers were used: two covered the visible range; one extended to 2500 Å in the ultraviolet; and the fourth covered the range 3000 to 12,000 Å. Commercially made photomultiplier coolers were used on all of these tubes. In the beginning they were cooled with dry ice and, later in the work, for long term stability, with cold dry nitrogen gas boiled from the liquid in a large Dewar vessel into which a heater had been dropped. Thermocouple monitoring allowed photomultiplier temperatures to be held approximately constant at about -85°C. This was important in the particular system employed for keeping the photomultiplier sensitivity constant.

The monochromator used with any of the photomultipliers as an entire detector unit had a small white diffusing screen mounted at one side of its exit slit. This screen was illuminated through a reproducibly mounted flexible light pipe by a small incandescent lamp operating at constant voltage from a stabilized dc supply. The voltage was constant to about one part in a thousand. The lamp was mounted inside a turret which provided for the interposition of neutral-density filters or a shutter between the lamp and the end of the light pipe. The voltage on each photomultiplier was maintained such that, with the appropriate neutral-density filter in place, an arbitrary 0.85-μA current was always shown by the detector at the beginning and end of any glow or standardizing source photometry. Because the detectors were exposed to the whole radiation from the lamp, which was brightest in the red, photomultiplier temperatures were kept constant to prevent suspected small shifts in their long wavelength threshold. Since 3914-Å photometry was involved in most of the work, perhaps the neutral filters should have been replaced by blue filters of various densities. Whether any variation in the experimental results is to be attributed to variation in pho-

tomultiplier sensitivity arising from shifts in wavelength threshold is not known.

Obtaining a suitably white and rugged coating for the interior of the sphere required considerable effort. The previous coating, a mixture of water, magnesium oxide, and a little carboxy-methyl-cellulose as a binder, was not uniform and was slightly yellow, probably from too much binder. The new coating, sprayed from a small gun, was a slurry of magnesium oxide in chloroform in which some lucite shavings had been dissolved and into which some lumps of dry ice were dropped during the spraying to chill the mixture and keep it interspersed. This coating, applied directly to the burnished aluminum surface, was adequately rugged and showed very good optical characteristics in reflectometer tests. It did, however, show further optical gain when over-smoked with burning magnesium. The smoke adhered well to the undercoat of magnesium oxide.

To provide for collection of charge injected into the sphere, strips of the metal surface were left bare. Since the brightest part of the glow occurs in the vicinity of the sphere polar region at the gun, since the standardizing radiation for calibration is directed in on the polar region opposite the gun, and since all photometer measurements are made against the sphere surface opposite the window, these regions were very carefully coated and no metal was left bare near them.

The bell jar (still referred to as such in spite of considerable dissimilarity) used in the new measurements is shown schematically in Fig. 2. It is a stainless steel box 12 in. high, 15 in. wide, and 18 in. long, with large openings at two sides and one end. The sides and end are closed by plates of either metal or quartz, vacuum sealed by O-rings. Except for the observation window, all interior surfaces were heavily blackened with acetylene soot. The gun is at the closed end of the box. The top and bottom of the box are well perforated with smaller vacuum-sealed openings to allow making various measurements with the chamber. The main pump hangs below the box, separated from it (in order from the pump) by a cold trap, a large vacuum valve, a Tee connection to the gun, and a thin butterfly valve. During measurements, the butterfly valve is closed so that the chamber is pumped only through the small orifice

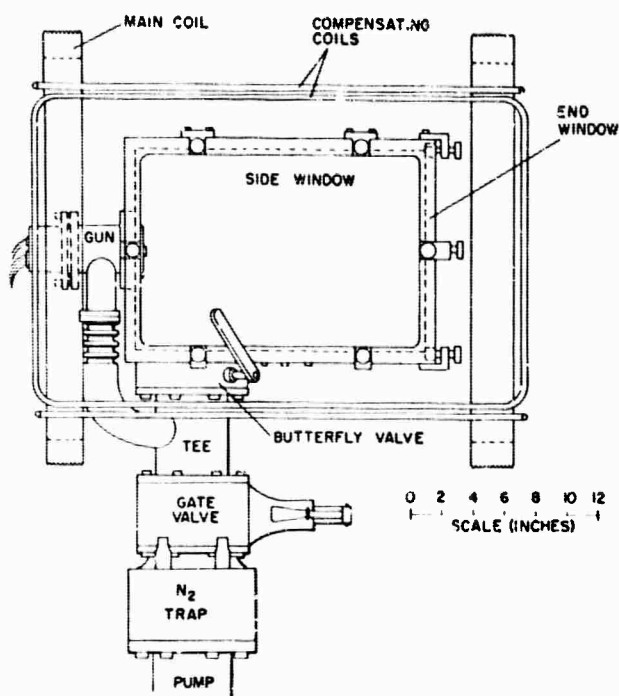


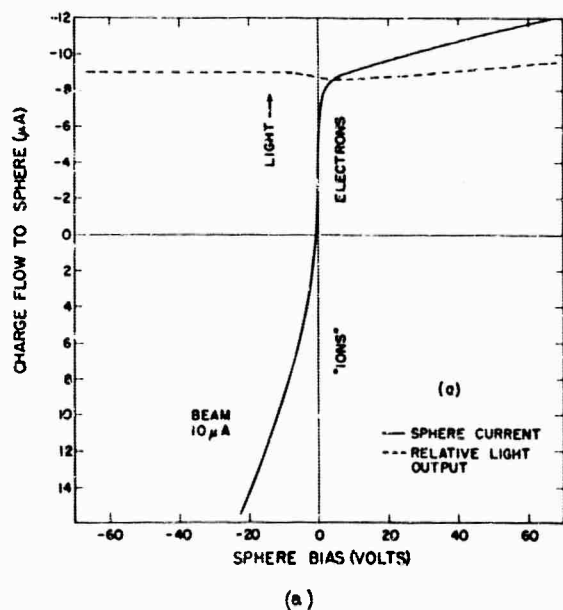
Fig. 2. Bell jar apparatus.

between gun and chamber through which the electron beam is injected. Gas leakage into the system is provided by a commercial leak valve. Pressure measurements are made using the electronics of the previously mentioned capacitive manometer, connected to a separate capacitance head fixed to the system.

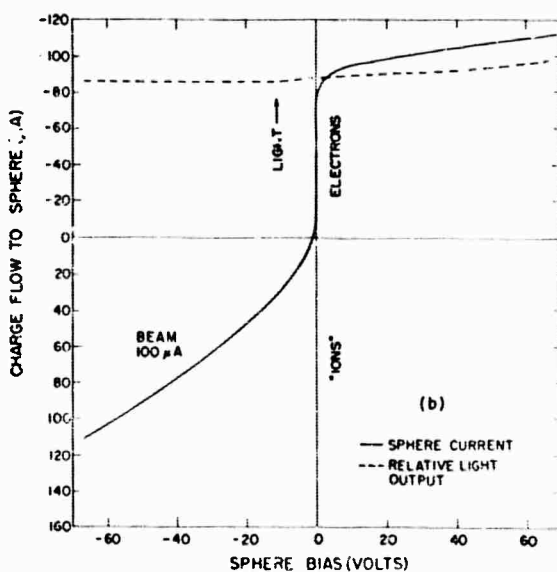
Coils at each end of the box allow fields of up to 50 gauss to be imposed over the volume (see Fig. 2). Smaller coils in the planes of the sides of the box permit compensation of the earth's field to keep the beam on the box axis.

BEAM CURRENT MEASUREMENT

From the beginning of the project, measurement of beam current, particularly in the integrating sphere, was difficult. Even with an apparently normal glow in the sphere, the currents leaving the gun and those entering the sphere (which can be metered, and should be equal) were both very low. By biasing the sphere relative to the gun head inserted into it, one could make the currents positive, negative, or zero. Evidently slow electrons and ions produced by the primary beam cause the variation. Characteristics of sphere current and light output vs sphere bias are shown in Fig. 3. Note that the light output is nearly independent of the sphere bias. The current characteristic drops below zero (positive current to the sphere) at negative bias as slow secondary electrons, far more abundant than primary electrons, are repelled from the sphere to be collected by the inserted gun head. Beyond the shoulder of the curve there is a slow rise, presumably because of the rejection of ions by the sphere. In



(a)



(b)

Fig. 3. Sphere bias characteristics for (a) 10-μA and (b) 100-μA beams (current assumed correct at 22-1/2-V bias).

the steep fall-off, the current is very unstable, probably because in this low bias region the slow electron flow is greatly influenced by the potential distribution over the insulating wall and time is required for equilibrium to be attained. The wall coating potential is not greatly different from that of the underlying metal.

In initial measurements, current readings were made with a positive 22-V bias applied to the sphere, the gun being grounded (through a meter). This operating point is well removed from the "shoulder." Since at 22 V the current characteristic is still slowly rising, this may not be the correct procedure. Perhaps some other bias would be more appropriate for the current measurement, or perhaps the rising characteristic should be extrapolated back to zero bias. (There was less uncertainty in the current measurement when the beam was injected into a metal chamber, or at least one with large metal areas such as the cylindrical glass bell jar with grounded metal ends.) Measurement of the current to a small grounded plate near the gun tip shows that when the sphere goes about 4 V positive, the current to the plate (and presumably that to the gun tip) becomes zero. Floating potential measurements of this plate and of the sphere itself indicate about a 4-V difference between them and the gun tip. Numerous other tests indicate that a bias of about 4 V is more appropriate than the 22 V used initially. Whether the value is independent of beam current and energy is not certain. The light output and beam current measured at different values of sphere bias are most nearly proportional at low values, and show a higher power dependence at higher biases. In later measurements we operated close to the "shoulder" of the current characteristic--at about 4 V--and allowed a small annular electrode placed in front of the gun nozzle to float. The floating electrode received no net current and helped prevent the flow of charge back to the gun. In calculating efficiencies from observations made with the sphere bias at 22 V, the beam current was corrected to that expected for 4-V bias based on current characteristics like those displayed in Fig. 3.

One rather remarkable experiment pointed up the difficulty of current measurement. A box made entirely of lucite, except for the fastening screws

(which did not penetrate the walls), was mounted in the bell jar up against the gun tip. A small hole at the gun orifice and a large hole in the top for pumpout, closeable by a lucite flap, were the only openings in the box. At low accelerating voltages (below 250 V) and at pressures comparable to those used in the fluorescence measurements, no current from the gun was detected and apparently no beam was injected, since no normal glow was observed. (A faint red glow seen near the gun port was apparently unaffected by the magnetic field. It is not understood.) With the top flap open, a normal glow appeared in the box, a red glow appeared in the hole at the top, and the gun current meter reading became about normal. At higher voltage, with the top hole either open or shut, there was a normal-looking glow in the box. Very little beam current was indicated until the top hole was opened, then the red glow appeared and the main fluorescent glow increased slightly in brightness and extent. With the top hole closed there was clearly enough charge flow back along the beam to balance the charge injection into the volume.

Although considerable time was spent in trying to improve the current measurements, not all the factors are thoroughly understood nor are criteria established for determining the true injected current under all conditions of pressure, beam current, and electron energy. Fortunately, the fluorescence measurements were made primarily at one energy and one pressure for which we are reasonably sure that the method used to determine the injected current is correct.

PHOTOMETRY

The photometric procedures for the integrating sphere and the bell jar were essentially the same and are indicated schematically in Fig. 4. An f5, 50-cm Bausch and Lomb monochromator, modified for scanning over wavelength with a belt drive powered by a multiratio gear box and a synchronous motor, was used. The light in the glow, within a certain bandwidth and at a particular wavelength, was compared to the light in the same bandwidth and at the same wavelength from a standard source. Differences in procedure for the two systems, caused by instrumental departures from the ideal, are mostly

in the corrections applied. No characteristics of individual components enter except in corrections; the sphere (or bell jar), monochromator, and detector are treated as one optical element. The system response to a known amount of radiation from a standard lamp is determined and used to determine the amount of radiation from the unknown source produced, a measured amount of output current. The monochromator position and slit width are not changed between the two measurements, and the photomultiplier sensitivity is kept fixed. The grating area is comfortably filled by the observation part.

For the calibrations with the sphere, the vacuum system is brought to atmospheric pressure and the gun is removed, exposing a $3/4$ -in.-diam aperture. The back polar region of the sphere is illuminated by a standard tungsten-iodine source placed 43 cm from the aperture and operated under specified conditions. The photocurrent is recorded as a monochromator scan is made over the desired spectral range. Blocking filters are used where necessary to remove second-order light. A similar scan is then made with a fluorescent glow present in the sphere. Spectral irradiance data supplied with the standard lamp allow determination of the power in the glow.

Corrections are necessary for a number of reasons. During efficiency measurements with the integrating sphere, there is always some fluorescence in front of the window. The contribution of this fluorescence must be subtracted from the observed signal. Also, the sphere surface seen through the observation window receives light directly from the diffuse glow in the volume, whereas in the measure-

ments with the standard lamp it is illuminated only by at least once-reflected light. Lastly, that area illuminated by the standard source has higher reflectivity than the average for the whole sphere.

The correction for the fluorescent glow before the window is found by looking at the glow (with the sphere removed) against a black surface on the far wall of the chamber. The correction, of course, varies with pressure and beam energy, but typically is about 4%. To make the other corrections, one must know the average reflectivity of the sphere and the relative intensities of direct and reflected light falling on the observed area. This depends on the source position, and is determined by moving a small lamp through the sphere. The lamp envelope is diffusely transmitting (for uniformity of illumination), and at its base is a small whitened mask. Lamp and mask are mounted at the end of a long rod so that when the rod is turned, the observed area sees first the lamp and then the mask. The illumination on the area for the two lamp orientations gives the contribution of direct light relative to that of light diffusely reflected to it. With the lamp at the center of the sphere, the two readings give the average reflectivity of the sphere. The glow is not uniformly distributed, so the necessary correction varies throughout the volume. Not knowing the glow distribution and wishing to avoid a very complicated integration, we obtained the position of the center of gravity of the glow from projected photometric plots of a similar glow in air at atmospheric pressure published by Grun.⁷ The plots were scaled up by the ratio of the ranges in the two cases. The correction for the directly reflected light was that which would be applied for a source located at the calculated center of gravity. While not exact, this seems a reasonable approach. The correction depends on the quality of the sphere coating, and varied in this work from 10 to 14%. The correction for the better-than-average reflectivity of the bright polar region is only about 1/2% and is straightforward, taking the reflectivity over that region to be about 98%.

For the bell jar photometry, the monochromator-detector is moved far enough away that the 18-in. length of the box, as projected through the entrance slit, fills the width of the grating. The corrections in the measurements are again necessitated by

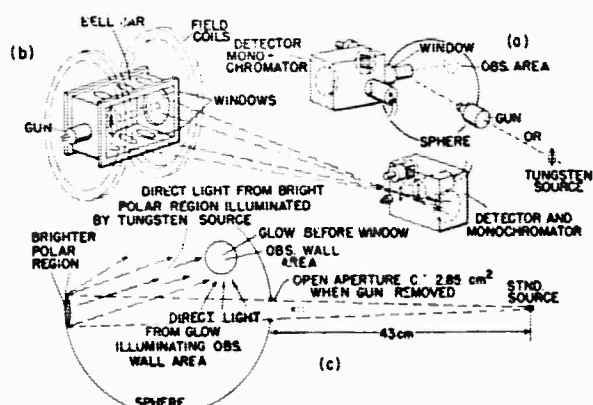


Fig. 4. The photometry of (a) integrating sphere and (b) bell jar. (c) Calibrations and corrections in sphere.

nonuniform source distribution and nonuniform response of the grating-photomultiplier combination to light from different parts of the glow. Having made the fluorescence measurement, where does one place the standard source for the calibration? We determined the center of gravity of the glow as seen by the monochromator-detector at the wavelength in question. This was done by taking moments of the spectrometer currents recorded while a slot was traversed horizontally and vertically across the window in front of the glow. The standard source was then located in the median plane at the position so determined. This can not be exactly correct, for one can imagine the extreme case in which, with the lamp at the center of gravity, the light projected from the nearly point standard source falls on a "dead" spot on the grating. The grating was found to vary smoothly over its surface at 4000 Å (it is quite different at 8000 Å) so the error is not large.

A difficulty in the bell jar calibration appears because the standard source is so bright that inordinately large photocurrents might be drawn from the photomultiplier. This was avoided by reducing the gain a set amount through reference to the signal produced by the sensitivity monitor lamp. To further relieve this problem, a neutral-density filter was used in front of the entrance slit of the monochromator in both the calibration and efficiency measurements.

FLUORESCENCE EFFICIENCY MEASUREMENTS

3914

The fluorescence efficiencies were determined principally at 70-μ dry laboratory air pressure (corresponding to 66 km altitude) and at an electron energy of about 750 eV. (In the bell jar they were determined at 670 eV with a 25-gauss applied field, set to prevent both wall and end losses.) A great many measurements involving all four photomultipliers in both systems have been made. Emphasis was on the 3914-Å fluorescence. The usual technique was to allow the monochromator to scan slowly over the molecular band, recording the output photocurrent. Event marks were made manually at the side of the trace every 50 Å. In calibration, a similar scan was made of light from the standard lamp. Wavelength marks on the two records were matched, and

the lamp signal was read at the position corresponding to the peak of the fluorescence signal. In many instances the monochromator was simply set at the peak wavelength, and the response to the lamp obtained at that point only. The area of the fluorescence band was determined by planimetry of the photocurrent trace. These data were converted to useful units by planimetry of a rectangle so many microamperes high and angstroms long on the chart. The power in the band is determined from the response to the known standard radiation. From this and from the known energy input in the beam, the efficiency is obtained. The spectral bandwidth is not needed because the slits were not changed between measurements with the two sources, but for most of the measurements it was about 66 Å. A typical band profile is shown in Fig. 5. Because of the changing response of the photomultipliers in this region (the response was assumed constant for the efficiency determination, and equal to that at the band center), the actual profile of the band near the base could be different from that shown. To determine a boundary for integration, the line profile was brought to zero on the short wavelength side immediately below the valley point, as shown by the dashed line in the figure. This probably underestimates the area on this side, and the line should probably be brought through a point halfway between the valley point and zero (as shown by the dotted line). On the long

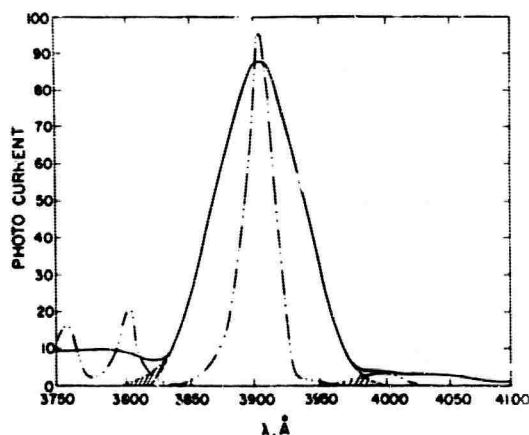


Fig. 5. Typical 3914-Å scan (with 6097S photomultiplier). Dashed line at base indicates envelope measured by planimetry. Dotted line indicates more probable real envelope on short wavelength side. Dash-dotted narrow profile is a 10-Å resolution scan of band. Shaded areas are compensating error areas indicated to justify method of approximating area of band.

wavelength side there is no clean criterion to apply, so the line was brought to zero under the slight inflection point (dashed line).

No correction for energy lost from the beam between the gun anode and the sphere has been made in any of the work. This loss cannot be serious in any runs except some made at high pressures for which the range is only an inch or so and the distance times pressure traversed by the beam in reaching the sphere is very appreciable. Two other corrections have been made in the laboratory work. The first is fairly large and is inferred by somewhat indirect means. This is a loss of light in the laboratory system that would not occur in the upper atmosphere, in that "back-scattered" electrons collide with wall surfaces before all their energy is expended in the gas. Use is again made of Grun's⁷ photometric contours of a glow produced by high energy electrons in air at atmospheric pressure, and of his plot of integrated light vs distance from the injection nozzle. This nozzle, being conical, allows him to obtain some light behind the injection plane. From planimetry of his published plot, one infers that at least 2.3% of the light occurs behind this plane. From the photometric plots one can estimate the ratio of this light loss to the loss to a spherical surface the size of our integrating sphere, scaled down in the ratio of his derived range to that obtained in some of this work six years ago. In the present experiment with the integrating sphere this light loss is about 11%. For the bell jar it is the 2.3%. No great accuracy can be claimed for either of these figures. That for the sphere may be somewhat large in view of recent range measurements which indicate that the assumed range is too long. In any event, our experimental efficiencies are increased by these factors.

Whether another correction should be made depends on what is wanted from the measurements. If one wants to know the efficiency for a practical detector with a bandwidth of 60 Å monitoring the upper atmosphere, a correction will not be applied. If one wants the efficiency for the production of light only in the 3914-Å, first negative (0,0) band of N_2^+ , a correction should be applied, for in the present measurements this band is completely unresolved from the 3884-Å (1,1) band. From a high resolution scan

over the region near 3914 Å made by Holland in this Laboratory, it has been determined that ~ 5% of the light in the two bands is contributed by the 3884-Å band. In the results to be quoted, both this and the preceding corrections have been made.

From nearly 130 scans made over the band in the integrating sphere, including all the corrections cited above, an average efficiency of $\eta_{3914} = 0.337\%$ was derived with a statistical accuracy of about 1%. This is greater accuracy than can be claimed for the actual value quoted, in view of the uncertainties in some of the corrections.

The reductions of the scans made with the bell jar are almost the same, differing a little only in the calibration. Instead of admitting a known amount of calibrating light into the system through a known aperture, one calculates the total power per 10-Å bandwidth that would be radiated by the standard source, if it radiated the same isotropically as in the direction prescribed for its use. The signal comparison then gives the power that the glow radiates in a 4π solid angle.

From about 30 scans made with the various photomultipliers and the bell jar, an efficiency value of $\eta_{3914} = 0.350\%$ is derived with a little less than 2% statistical accuracy.

To obtain the best efficiency value statistically, one should probably weight the integrating sphere result about three times as heavily as that of the bell jar. But because of the size and uncertainty of the corrections applied to the sphere results, one is inclined to weight them about equally. This leads to a final value of $\eta_{3914} = 0.343\%$ and the belief that this value is good possibly to 5%.

Total Fluorescence Efficiency

A number of scans of the fluorescence in the spectral range 3000 to 11,000 Å have been made with the integrating sphere, using the red-sensitive photomultiplier. Blocking filters were used where necessary to eliminate second- or third-order light. To correct for light contributed to the glow scan by the gun filament's shining into the sphere, a single scan of this light alone was made for each run. This signal was subtracted from the glow scan. A similar calibrating scan of the standard lamp

radiation was made for each run. In each run, an average of two or three lamp and fluorescence scans was taken. From the standard lamp scan and the data supplied with the lamp, the response ($\mu\text{W}/10 \text{ \AA}-\mu\text{A}$) of the detection system vs wavelength was plotted. From this response and the fluorescence scan reduced by subtracting the filament light contribution (each corrected for base line drift, scattered light contribution, and any appreciable photomultiplier sensitivity change), a power plot of the fluorescence spectrum was drawn. Planimetry provided the power ratios in various parts of the spectrum--in particular the ratio of the power in the combined 3914- and 3884- $\text{\AA}$ bands to the total. A subsequent scan and calibration with the ultraviolet photomultiplier made possible an extension of the spectrum to short wavelengths. Using a chopped electron beam and ac synchronous detection, the spectrum was extended to 12,000 $\text{\AA}$. Direct current calibration at this wavelength was possible by careful subtraction of scattered light contribution. Data on the standard lamp were obtained by extrapolation from the region below 11,000 $\text{\AA}$. Each of these spectrum extensions was normalized at a strong band common to the usual scan and the extension. This required only a small adjustment, but it means that the absolute magnitude of the sensitivity for the long and short wavelength scans is essentially based on the better calibration in the central region, while the wavelength dependence of the sensitivity is determined by the extension calibrations.

In determining the total efficiency we assume that the correction for fluorescence in front of the window is the same at all wavelengths as it is at 3914 $\text{\AA}$, and that the corrections for the differences in illumination of the magnesium oxide surface of the integrating sphere are also independent of wavelength. This is not actually so since the reflectivity involved in these corrections does change with wavelength. Within these limitations, one derives (for four separate calibrations and spectrum scans) ratios of the power in the 3914- and 3884- $\text{\AA}$ bands to the power in the spectrum, from 3000 to 11,000 $\text{\AA}$, of 0.200, 0.196, 0.205, and 0.202 for an average value of 0.201. Adding the small amount of light in the extensions to long and short wavelength, one obtains a total efficiency, over the region

2500 to 12,000 $\text{\AA}$, of $\eta_T = 1.86\%$.

Efficiencies in Other Bands

Efficiencies in selected spectral features other than the 3914- $\text{\AA}$ band were obtained as an afterthought in the total efficiency determination. In each of several spectra, areas of the bands of interest were measured and compared with the area of the 3914- $\text{\AA}$ band in the same spectrum. Since a good value had been obtained for η_{3914} , efficiencies of the other bands could be determined.

Unfortunately, most total spectrum scans were made with a lower chart speed and a higher spectrometer scanning speed than was employed in scans across the 3914- $\text{\AA}$ band alone. Thus spectral features were narrowed so that area determinations are less reliable than in the 3914- $\text{\AA}$ photometry. Furthermore, for all scans except the two made at high resolution, relative intensities were determined by measuring areas in the (derived) power spectra, rather than by measuring areas in the photocurrent records and converting to power as in the 3914- $\text{\AA}$ photometry. For the two high resolution scans, band areas were measured in the photocurrent trace and converted to power using calibration data appropriate for the wavelengths at the peaks of the bands. Corrections to all measurements were the same as those applied in the total efficiency determination.

Data and results are presented in Table I. Each spectral feature is identified by band system, bandhead wavelength of the principal constituent, and vibrational quantum numbers of bands which contribute to the intensity. The ratios of power in each band complex to that at 3914 $\text{\AA}$ are tabulated. Efficiencies listed are the power ratios multiplied by 0.357%, the efficiency of the 3914- $\text{\AA}$ feature. (This feature includes the 3884- $\text{\AA}$ band, and its efficiency is 1.05 times the value of 0.34% obtained for the 3914- $\text{\AA}$ band alone.)

While there is rather a wide spread in the ratios for particular bands, the average deviation from the mean is only 4 to 6% for all except the 3159- $\text{\AA}$ band in the first seven runs listed. Results of the high resolution scan with the 7102 photomultiplier, where some separation of components of complex features was possible, are not very

Table I. Power Ratios of Indicated Spectral Features to 3914-Å Feature and Calculated Efficiencies:
Air Pressure 70 μ , Electron Energies near 750 eV.

PM type-- Run	N ₂ 2P					N ₂ ⁺ 1N	N ₂ 1P		
	3159 Å (1,0) (2,1) (3,2)	3371 Å (0,0) (1,1) (2,2)	3577 Å (0,1) (1,2) N ₂ ⁺ -1N (1,0) (2,1)	3805 Å (0,2)	4059 Å (0,3)	3914 Å (0,0) (1,1)	8723 Å (2,1)	8912 Å (1,0)	10,510 Å (0,0)
7102--A	0.362	0.319	0.333	--	--	1.0	0.233	0.260	0.177
7102--B	0.188	0.380	0.375	--	--	1.0	0.208	0.241	0.178
EMI--UV	0.275	0.365	0.326	--	--	1.0	--	--	--
7102--C	0.287	0.384	0.365	--	--	1.0	0.200	0.211	0.155
7102--D	0.228	0.397	0.358	--	--	1.0	0.193	0.219	0.149
7102--E	0.332	0.369	0.369	--	--	1.0	0.208	0.231	0.167
HRS*,EMI--UV	0.229	0.332	0.368	0.084	--	1.0	--	--	--
Average	0.272	0.364	0.358	0.084	--	1.0	0.209	0.231	0.167
Efficiency %	0.097	0.130	0.128	0.030	--	0.357	0.075	0.082	0.060
	(1,0) only	(0,0) only	(0,1) only						
HRS*,7102	0.354	0.390	0.322	0.103	0.0336	1.0	0.213	0.229	0.204
Efficiency %	0.126	0.139	0.115	0.037	0.0120	0.357	0.076	0.032	0.073

*HRS: "High" resolution scan.

satisfactory. The efficiency of a component can hardly be larger than that of the complex. However, even in this run, ratios for the first positive bands agree reasonably well with the average of the low resolution scans.

Variation of Efficiency with Beam Energy

Most of the efficiency data were obtained in a restricted energy range near 700 eV and at 70- μ pressure. Some studies at other energies were made for comparison. This is of some interest since a theoretical calculation⁸ indicates that an increase by about a factor of two may be expected in going from primary electron energy of 100 eV to 1000 eV. The measurement is relatively easy to make. The monochromator-detector observing the sphere wall is

set at the peak of the 3914-Å fluorescence. Assuming that the height of the photomultiplier current peak is proportional to the total band intensity, one observes the variation in detector output as the electron beam energy is varied at a constant input current. If the pressure is held constant, the glow diminishes in size drastically as the beam energy is reduced. One might think that a variation merely reflected an increase in the sphere reflectivity toward the polar region of the gun, where even an extended glow is most bright. However, the experiment can be done in another way; the pressure can be decreased along with the decrease of beam energy, so that the volume of the glow is kept approximately constant. Figure 6 shows the results of both techniques. In addition, there is a plot obtained with the bell jar glow held at constant size. The dashed

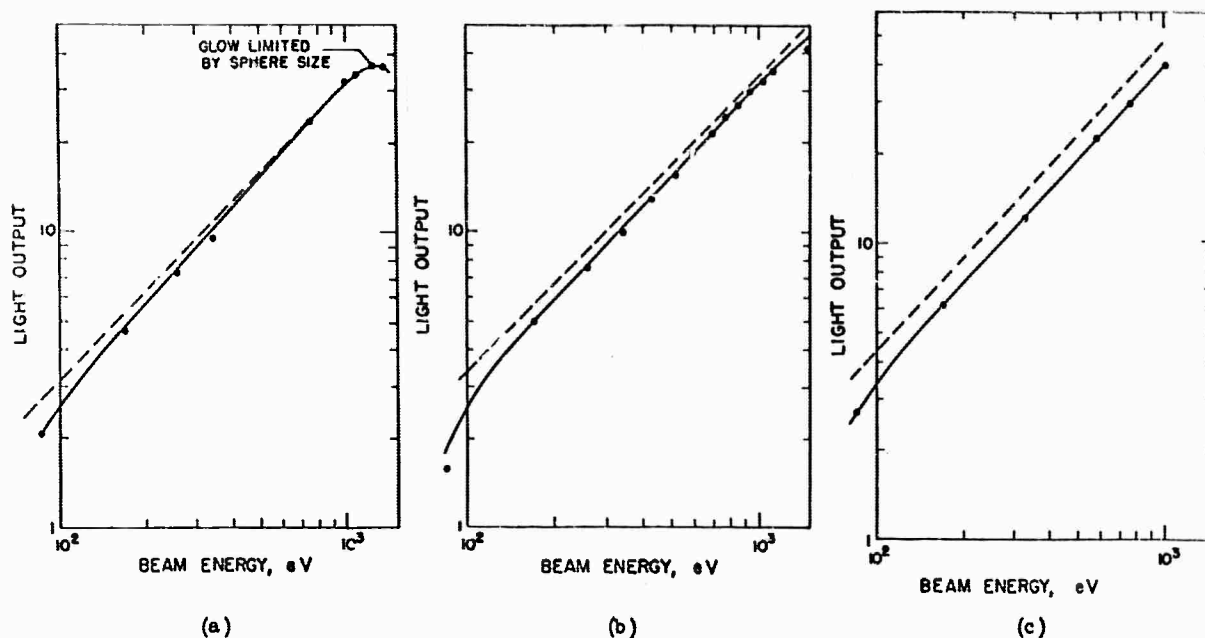


Fig. 6. 3914-Å fluorescence vs beam energy. (a) Sphere - constant pressure, (b) Sphere - constant glow size, (c) Bell jar - constant glow size. Average slope ≈ 1.07 . Dashed line corresponds to constant efficiency.

line beside each plot indicates what would be expected if the efficiency were constant. The light output apparently increases a little faster than the energy (about as the 1.07th power of the energy), and this result is not greatly changed by altering the pressure during the run. The light output from the bell jar appears more nearly proportional to energy than that observed from the sphere. Except for the low point at 85-eV beam energy, the change in efficiency over the range is not more than 1.2 to 1.

Variation of Efficiency with Pressure

As a corollary to the preceding discussion, one can perhaps say something about the pressure dependence of the efficiency. The efficiency seems quite independent of the pressure below 100 μ . When new range measurements indicated that the efficiency could be measured at pressures below 70 μ , one careful absolute measurement was made at 40 μ . This involved a new sphere calibration and corrections and a new correction for fluorescence front of the observing window. But no new correction was made for the loss of the back-scattered electrons, which is probably greater at the low pressure. Applying

the old back-scattering correction gave a 3914-Å efficiency of 0.35%. A proper correction would raise this value to perhaps 0.38%.

The best evidence that the efficiency does not depend on pressure below 100 μ is in the curves of energy dependence, where pressure is also varied to maintain constant glow size. In these circumstances the back-scattered loss and window corrections are about constant.

Of slight possible interest is the fact that the efficiency is independent of gas flow rate into the sphere if the pressure gauge reading is held constant. Pressure gradients and wall impurities appear to be negligible factors in the results.

At pressures from 100 μ to 2 mm, there is marked degradation of the efficiency, if the spectra to be presented later are correct. (See the section, "Spectral Variations with Pressure.")

Efficiency in Nitrogen

One careful absolute measurement of the 3914-Å efficiency in nitrogen was made. It was made near the middle of a long period separating two calibra-

tions of the sphere, during which period the sphere showed an average reflectivity deterioration of about 13%. Taking the sphere deterioration to be half of this at the time of the measurement, and scaling the derived efficiency down by 78% to correspond to the efficiency in air, one arrived at an efficiency of 0.33%. The procedure is not a happy one.

More significant is a series of measurements on the 3914-Å relative efficiency made in the bell jar as the nitrogen ratio in an atmosphere of oxygen and nitrogen was varied from zero to 100%. The results are shown in Fig. 7. It seems clear that the oxygen has no effect in deactivating this particular excited state of nitrogen, at least at the 60-μ pressure of this experiment.

As a point of interest, a search failed to reveal the auroral green line in the pure oxygen atmosphere, even at pressures in the micron range and at 10-Å resolution, although the (1,0) band of O_2^+ at the same wavelength was itself quite bright, as was the (2,0) band at shorter wavelength. A measurement of the collision cross section for the excitation of these two states might be of considerable interest, but time has not permitted it.

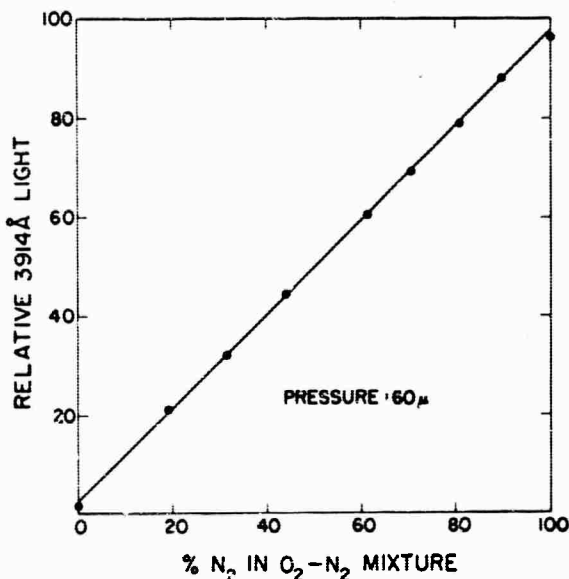


Fig. 7. 3914-Å production vs N_2/O_2+N_2 ratio. The line misses the origin probably because of residual N_2 in outgassing.

Efficiency Measurement with Interference Filter Photometer

Electron excitation cross-section measurements for the 3914-Å band of nitrogen have been made by R. Holland of LASL Group J-10.⁹ His results and those of some others doing similar work seem to disagree. Since photometry is very much involved, we decided to see what efficiency his photometer would give for a glow produced in our bell jar. The photometer utilizes an interference filter to isolate the band at 3914 Å (free of that at 3884 Å) and, by baffling, looks at a small solid angle. To use it for a fluorescence measurement with the bell jar necessitated reflecting the light once in a mirror in order to fit the setup into a single laboratory room. The reflectivity of the mirror was measured later, but the bell jar quartz window transmission was simply taken as 92%, representing only the reflection losses. A number of measurements made at 670-eV beam energy in air at 70 μ and corrected for the back-scattering loss gave an efficiency value of 0.34%. The agreement is too good, but does lend confidence in the photometry of both programs.

Variation of Efficiency with Beam Current

As indicated previously, in trying to establish a correct operating value for the integrating sphere bias, a great many plots of light (3914-Å) vs beam current have been made. Most of these plots gave a light variation a little steeper than the first power of the current, with the exponent ranging from a very satisfactory value of unity up to 1.08. Typical is a light variation proportional to the 1.04th power of the current. Extensive measurements have not been made in the bell jar, although some recent measurements indicate a close to linear dependence over two decades. Bell jar results of six years ago over five decades, from 10^{-3} to 100 μA, showed a nearly linear dependence. This experiment was later extended by Holland,¹⁰ under conditions intended to increase the probability of secondary excitation of N_2^+ . Nitrogen at 70-μ pressure was bombarded by a beam of 840-eV electrons injected parallel to a 200-gauss magnetic field. Emission at 3914 Å was monitored while beam currents were varied from 10 μA to

5 mA. Light output in the 3914-Å band was proportional to current over this range. If there is any secondary excitation in the present fluorescence measurements, it is only a small factor in the final results quoted above.

SPECTRA

"High Resolution" Spectrum

After low resolution spectra of the fluorescence had been obtained in making total efficiency measurements, it was suggested that a higher resolution scan of the spectrum be made for permanent record. Accordingly, the monochromator slits were narrowed to about 1/4 mm, corresponding to a theoretical resolution of about 8 Å (actual resolution is probably about 10 Å). Since this represented a large drop in light input to the instrument below that at 2-mm slit width, the electron beam was chopped and synchronous detection used. The scanning rate was slow to allow sufficient integration time for noise reduction. Only one such spectrum has been made, the run taking about 10 hours. Another would be useful to check on some minor features which may be noise. The ratio of photomultiplier noise to signal is everywhere at least two to one, so it is possible that some of the spectral fluctuations are not real. In determining the power at any wavelength, we assume that corrections for the window glow and for the effect of direct illumination of the observed area are independent of wavelength. The latter is certainly not true since it involves reflectivity of the sphere which does change with wavelength. Whether the ratio of light emitted at the window to that diffusely reflected out of it is a function of wavelength is not certain, but there is some evidence that in the peripheral regions of the glow the red light increases relative to that of the 3914-Å band. The effects of assuming these corrections to be independent of wavelength cannot be very serious, however.

The chart record of the photocurrent spectrum was smoothed out, and data from it and the calibration scan (including corrections for dark current and base-line drift in the latter, which was a dc measurement) were put on punched cards and fed into

a computer.* The machine plotted a spectrum on a logarithmic scale. Figure 8, in three parts, shows the results. The spectrum differs from those obtained by Davidson and O'Neil¹¹ at much higher pressures and energies, but is not much different from one they obtained in nitrogen at pressures comparable to that used here.¹² The band identification is taken from their work and from Pearse and Gaydon.¹³ The spectrum will be of most use in the comparison and identification of bands observed in high altitude shots. The dotted portions of the spectrum at each end were obtained at much lower resolution in the work on the total fluorescence. These portions were normalized to the main part of the spectrum by matching strong features in the overlap regions.

Spectral Variations with Pressure

To determine whether there was observable collisional deactivation of the fluorescence in the laboratory system and whether it depended on wavelength (and how) over various regions of the spectrum, a number of spectral scans were made with the integrating sphere, over as wide a pressure range as feasible. These scans were made at energies of 750 and 1425 eV at a constant average beam current (the beam was chopped and synchronous detection used) of 100 µA in all cases. The problem of beam-current measurement again arose. Below 100-µ pressure the 4-V sphere bias previously determined appeared about right for the current measurement. At higher pressures the proper bias became less and less certain. Therefore, characteristic curves of sphere current vs bias voltage were plotted at each pressure, and the "correct" bias was chosen as the shoulder point where the curve breaks toward saturation. This break becomes less and less distinct and moves to higher and higher (always positive) bias values as pressure increases. Whether the true injected current was that read at the bias decided upon is a moot question. The need for a technique to ensure knowledge of the injected current is obvious.

The spectra presented are merely smoothed versions of the recorded photocurrents, with no

*Grateful acknowledgment is made to Lois Duncan for punching the cards and to Dorothy Stam for working out the program.

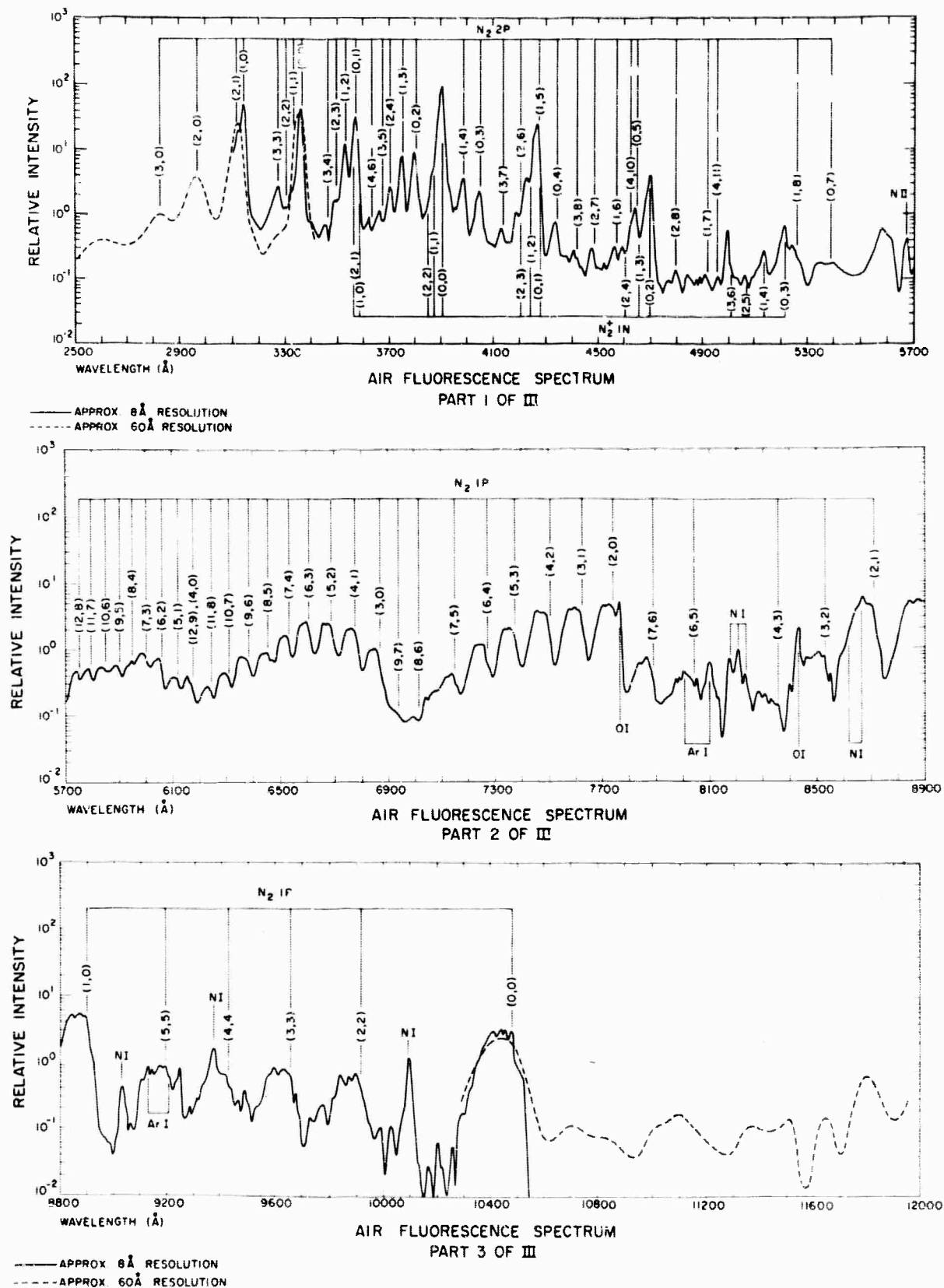


Fig. 8. Air fluorescence spectrum at about 8-Å resolution. Electron energy 850 eV, and air pressure 70 μ .

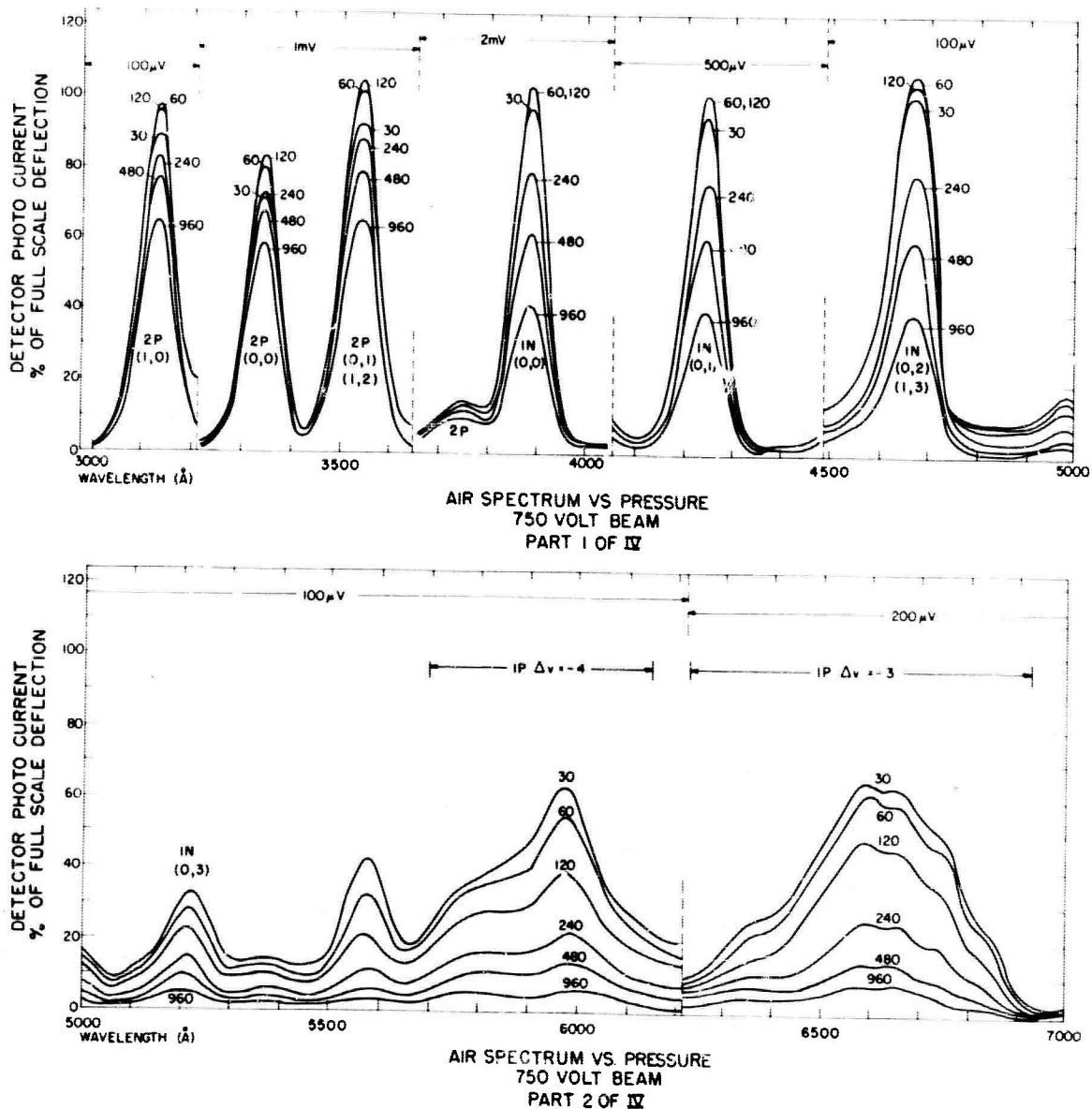
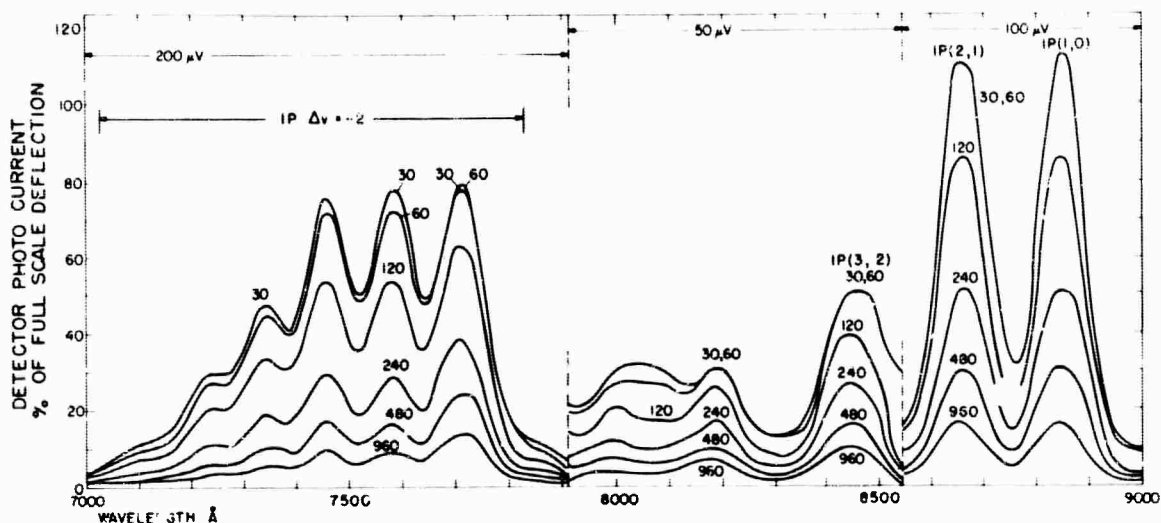


Fig. 9. Air fluorescence spectrum at various pressures for an electron energy of 750 eV. Note the initial rise in light output in the second positive and first negative systems with the pressure change from 30 to 60 μ . This is because at 30 μ the range is too long and not all the energy is dissipated in the gas. In spite of this the first positive system for the most part already shows a drop in light output over this pressure increment. Sensitivities for full scale deflection are indicated along the top of the spectrum.

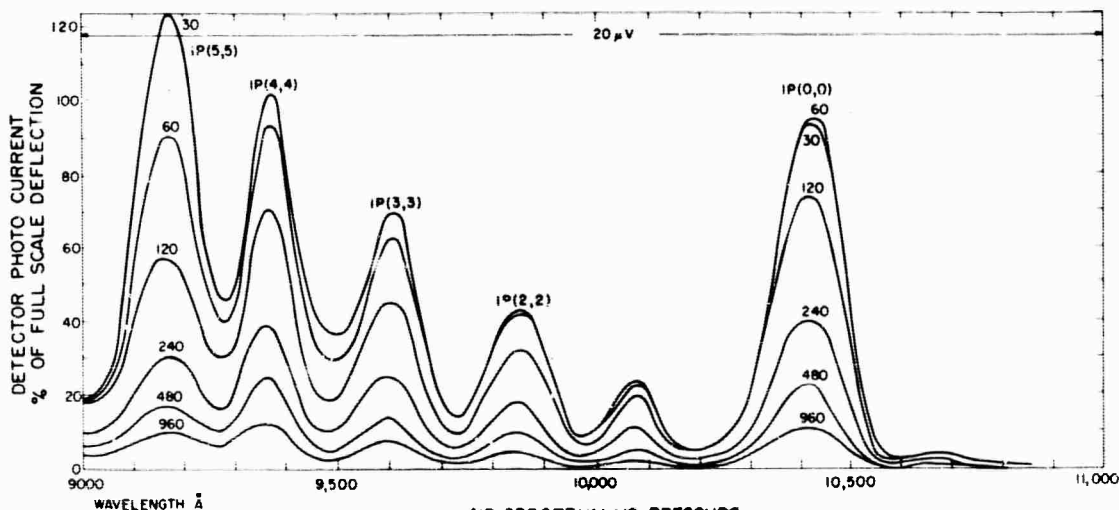
corrections applied. The corrections are implicitly assumed to be independent of wavelength and pressure. One is only interested here in how the various spectral features change with pressure. The window glow correction changes with pressure, but since it is only 4% at 70 μ and decreases at higher pressures, the error is not serious. Figure 9 shows the results at 750 eV. The results at 1425 eV are similar.

All the spectral features appear to be degraded with increasing pressure, but at different rates. The first positive system of N_2 falls off most rapidly, then the first negative system of N_2^+ , while the N_2 second positive system holds up best.

Relative peak heights (from the photocurrent record) for representative bands at various pressures are given in Table II. The height of each



AIR SPECTRUM VS. PRESSURE
750 VOLT BEAM
PART 3 OF IV



AIR SPECTRUM VS. PRESSURE
750 VOLT BEAM
PART 4 OF IV

band is taken as unity at 60-μ pressure. Band efficiencies at this pressure should be close to those given for 70 μ, with the possible exception of the first positive bands. Judging from the evidence in Table II, first positive efficiencies will be somewhat higher at 60 μ than at 70 μ. If one can reliably establish how any one of the systems actually depends on pressure, he can determine the dependence of the others from a detailed reduction of the spectral data. A factor which is ignored is the loss in beam energy between the gun anode and the sphere. At high pressures, this is certainly appreciable. It is estimated that, at 1 mm pressure, a 750-eV electron loses about 7% of its energy before enter-

ing the sphere.

Measurements from 3000 to 4000 Å in the bell jar over a somewhat smaller pressure range indicate that the degradation observed there is quite similar to that seen in the sphere. One feels a little more confidence in the current measurements made in the bell jar, so it may well be that the variations observed in the sphere are not far wrong. Beam energy loss between the gun anode and the interaction volume would be similar for the bell jar and the sphere.

Meinel Bands

The Meinel bands have been observed in one high altitude test. Attempts to see them in the laboratory

Table II Dependence of Selected Bands

Wave-length (Å)	3159	3371	3577	3914	8723	8912	10,510
System	N ₂ 2P	N ₂ 2P	N ₂ 2P	N ₂ 1N	N ₂ 1P	N ₂ 1P	N ₂ 1P
Pressure (μ)	---	---	---	---	---	---	---
50	1.00	1.00	1.00	1.00	1.00	1.00	1.00
120	1.01	1.03	1.00	0.98	0.79	0.78	0.78
240	0.85	0.90	0.86	0.76	0.47	0.46	0.44
480	0.30	0.83	0.78	0.60	0.28	0.28	0.26
960	0.68	0.73	0.64	0.40	0.15	0.14	0.13
Efficiencies at 70 μ (See Table I)	0.097	0.130	0.128	0.34	0.075	0.082	0.060

system were moderately successful. Since they are strongly collisionally deactivated, the observations were made with 750-eV electrons at pressures from 50 μ to as low as feasible. The technique was to scan selected spectral regions of the Meinel system and some other spectral feature that was not strongly collisionally deactivated. The (0,0) first positive band of N₂ was chosen as the reference band against which to compare the Meinel bands at various pressures. [The N₂ 1P (0,0) band does not have a very short lifetime, but does have a very low collisional deactivation cross section, so it serves well.] The work was done both in pure nitrogen and in air. The emergence of the Meinel bands at low pressure was most striking in the nitrogen scans, but similar behavior was observed with air. To get as long an electron path in the gas at low pressures as the sphere would allow, the beam was sent through a small bending electromagnet mounted in the sphere at the beam entrance port. In the presence of the applied longitudinal field, the beam became a helix, the pitch and diameter of which were easily variable--quite a pretty sight when observed without the sphere in place. The ploy was not as successful in increasing the light output as hoped, but spectra were obtained with it nonetheless. Figure 10 shows the results for some Meinel bands. All curves represent uncorrected photocurrent vs wavelength, normalized to the 10,510-Å (0,0) 1P band and plotted on

a logarithmic scale. Relative to the reference band, the Meinel system intensity increases by roughly a factor of ten over the pressure range. No quantitative analysis of the data has been made, and it seems that at best only the ratio of the deactivation rate for the Meinel system to that for the reference band could be obtained. This might be of some interest, however.

CROSS-SECTION MEASUREMENTS

We decided to determine whether some of Holland's cross-section values for the excitation of the 3914-Å band could be obtained in the sphere and the bell jar, to check that his values were reasonable.

Integrating Sphere Measurements

The cross-section measurement is simply an efficiency measurement made at low pressures so that the beam suffers little energy loss in traversing the interaction region--in this instance the diameter of the sphere. Thus pressures below 10 μ were used. At 10 μ, a 750-eV electron has a range of about four times the sphere diameter, so it loses approximately 30% of its energy, making a not very clean experiment. On the other hand, the cross section does not change greatly from 750 to 500 eV, so a rough check can still be made.

Because of some uncertainty in the capacitance manometer's most sensitive (0- to 3-μ) scale, the change in light output for small pressure changes was determined and the cross section appropriate for the observed differences was calculated. Excellent agreement with Holland's results was achieved. This was disregarded, however, when work was done with the bell jar and the apparent role of secondary electrons in producing light was recognized. The sphere was recalibrated, and the cross section was redetermined and found to be much too high. It is apparent from the bell jar work that the integrating sphere cannot give a good value, because it integrates light produced by secondaries as well as primaries, and there is no way to discriminate between them.

Bell Jar Measurements

When cross-section measurements were made in

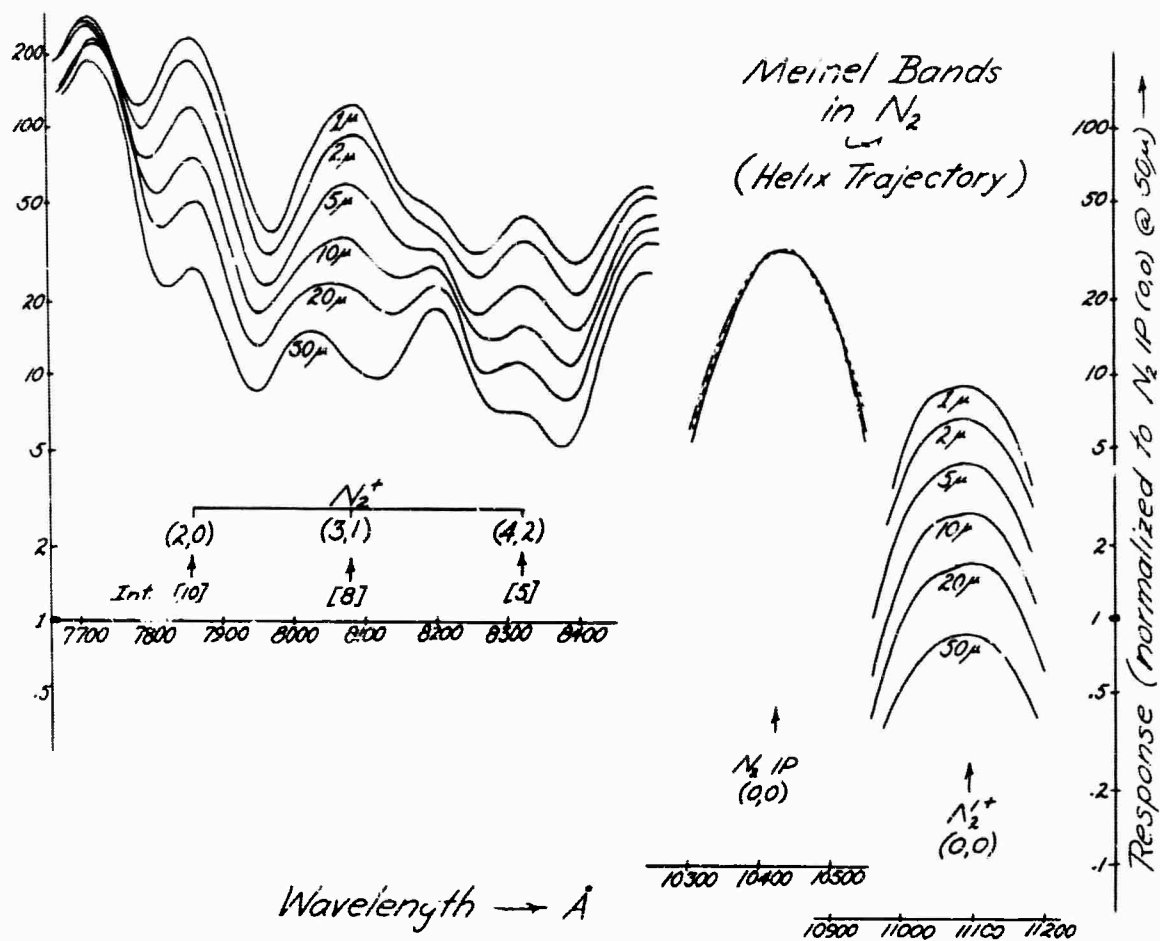


Fig. 10. Meinel band enhancements at low pressure (all features normalized to constant (0,0) LP band height).

the bell jar, more trouble was encountered. Holland's photometer gave results in reasonable agreement with his previous measurement. With our spectrometer, however, cross sections about 50% higher were obtained, though the two instruments had agreed in the fluorescence efficiency determination. We found that by shutting off all the light from the bell jar except that emanating from a narrow strip coincident with the primary beam, we could obtain cross sections in good agreement with Holland's results. The volume of gas external to the beam contributes a large part of the total light in the bell jar, and this light should not be included in cross-section measurements. Application of a magnetic field increases this external glow by keeping charged products away from the chamber walls.

The bell jar measurements with the spectrometer gave a value of about $7.5 \times 10^{-18} \text{ cm}^2$ for the

cross section at a beam energy of 670 eV, which compares favorably with Holland's best (interpolated) value of $7.15 \times 10^{-18} \text{ cm}^2$ at this energy. A series of measurements with his photometer on the bell jar also yielded a value of $7.5 \times 10^{-18} \text{ cm}^2$.

Origin of the External Glow

It is clear that at low pressures about half of the 3914-Å light is emitted external to the primary collimated beam. This is a surprisingly large amount, and the question arises as to its origin. We infer that it comes from the secondary electrons produced by the primary beam. More quantitative measurements on the fraction of light external to the beam were made by occulting the primary beam from the monochromator's field of view with a strip of black masking tape placed on the window of the bell jar. With a 25-gauss field applied to bring

the faint glow in from the walls, the 3914-Å light observed was about 40% of the total, at pressures of 0.5 to 6 μ . For the first positive (0,0) band at 10,510 Å, the external light is about 65% of the total. Higher magnetic fields reduced the light because more of it was then being produced behind the occulting strip.

It does not seem that this amount of light can come from primaries scattered out of the beam. The fact that at low pressures the beam does not greatly diminish in intensity as it traverses the chamber shows that not many electrons leave the beam, and the beam spread indicates that any scattering is largely small angle scattering. The pressures are such that the range is from 10 to 50 times the bell jar chamber length, so that scattered primaries do not lose much of their energy before striking the side walls. One trouble with the supposition that the light is due to secondary electron excitation is the relatively large extent of the glow in the 25-gauss field. One might expect even a 50-eV secondary electron to be bent into a circle of no more than 1-cm radius. If the glow is produced by secondaries, it is not clear why it extends to about 10 times this radius. The glow dimension seems to support the idea of glow production by scattered primaries.

This light was studied as a function of pressure. The secondary production and primary scattering per unit length of beam should change linearly with pressure. Light per unit volume produced by the secondaries or scattered primaries should then increase as the square of the pressure. On the other hand, if the secondary loses all its energy in the gas, the total secondary light would change only linearly with pressure--the primaries can hardly be expected to lose all their energy before meeting a wall. The actual dependence observed was between linear and quadratic, so the question is still open. The fact remains that considerable light is produced outside the primary beam.

RANGE MEASUREMENTS

Since visual measurements made six years ago gave ranges considerably longer than those arrived at by theory and about 20% longer than those meas-

ured by Lehman and Osgood¹⁴ in the 1920's. Further range measurements made during the present year are probably worth reporting, though the previous ones were not.

Range Measurements in the Integrating Sphere

The plot of light output vs energy at constant pressure and constant current in the integrating sphere (Fig. 6) shows a rather sharp break into saturation at a critical voltage. Actually, if carried to higher voltages, the curve tends downward. One imagines the efficiency to be constant, the total light increasing in proportion to the energy. However, at that electron energy where the beam begins to expend energy in the walls surrounding the glow, the light should begin to fall off. Studying this break point as a function of energy will, in principle, allow one to determine the pressure corresponding to the fixed range as a function of energy. Making the determination for two different spectral bands, as was done for the 3914- and 10,510-Å bands, allows one to determine whether the range is different for different excitations. In the experiment here, the energy was kept fixed and the pressure was changed to effect the change in range. The arguments are similar; it is the optical analogue of Lehman and Osgood's experiment. Typical plots are shown in Fig. 11. Although the break points obtained by extrapolating the straight parts of the curve agree well, the light outputs in the two bands vary differently with pressure. That in the 3914-Å band is very nearly proportional to pressure, and that in the 10,510-Å band exhibits a 1.4th-power variation. The latter curve also breaks less sharply. Both of these facts suggest that the ratio of red to blue light is higher in the outer reaches of the glow. This is also evidenced by the pronounced reddening of the glow seen when the peripheral regions are compressed toward the beam by application of a magnetic field. The ranges, however, seem to be the same, judging from the (extrapolated) break points. A plot of the pressure vs voltage for a fixed range equal to the sphere diameter is shown as (A) in Fig. 12, along with our other experimental curves (B) and (D) (see next section) and that of Lehman and Osgood (C) scaled to the sphere diameter. The integrating sphere results would show better

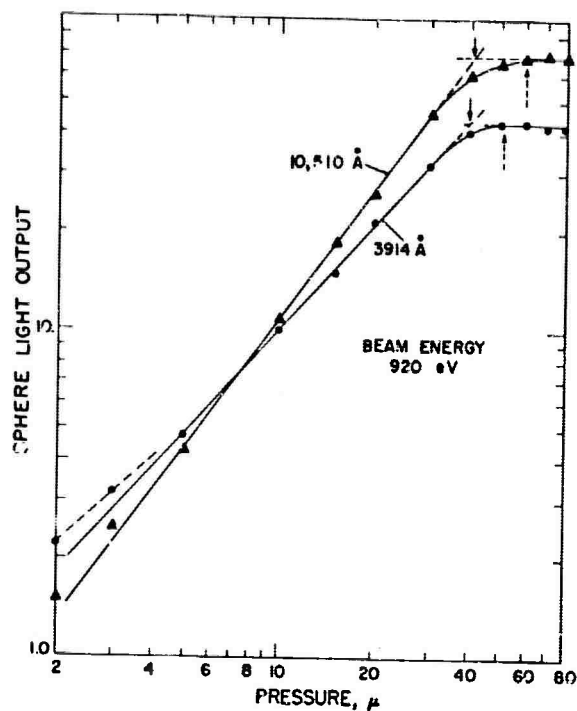


Fig. 11. Sphere light output vs pressure at 920-eV beam energy. Critical pressure taken at the solid arrows is $40\ \mu$ for range equal to 34-in. sphere diameter. Pressures at dashed arrows are in better agreement with range measurements by other methods.

agreement with other methods if the critical pressure were taken at the dashed arrows in Fig. 11.

Range from Narrow-Field Observations from the Side

Another, and probably more reliable, method of range measurement is similar to the visual method of estimating the range by measurement of the distance the glow extends from the gun. A photometer with a field of view narrow in the horizontal direction is fixed at one of the windows of the large vacuum chamber with the sphere removed. The photometer views the glow from the side, receiving light from a thin, wedge-shaped volume perpendicular to the beam axis. The detector is an unfiltered photomultiplier sensitive in the visible and near-ultraviolet range. Intensity measurements are made as the range is varied by changing the beam energy, with the pressure and current kept constant. As the beam energy decreases, the light falls off as shown in Fig. 13. The light decreases linearly over a good part of the

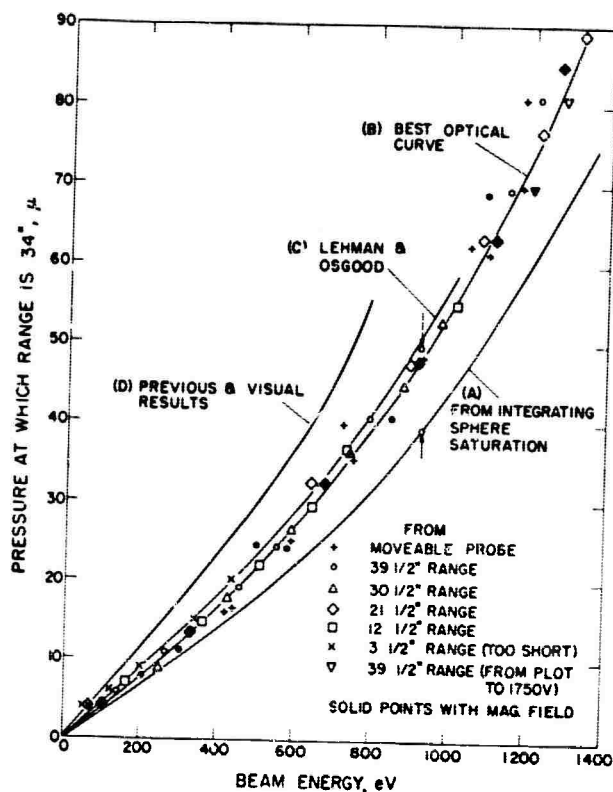


Fig. 12. Pressure-voltage plot for fixed 34-in. range. The two circle points indicated by arrows (solid and dashed) are the critical points from the 3914-Å plot of Fig. 11 correspondingly marked.

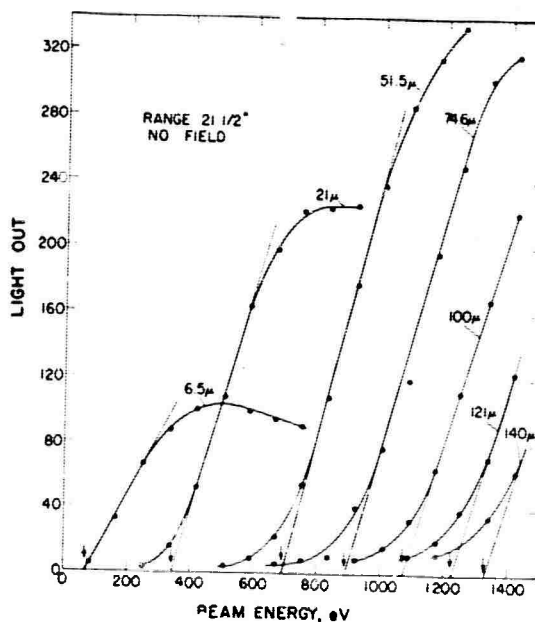


Fig. 13. Light signal vs beam energy at various pressures for the fixed photometer with a narrow field of view. Arrows indicate critical voltage at which range is 21-1/2 in.

energy range before it tails off, so an extrapolation to zero light output can be made and a reproducible and definite energy value obtained. For this electron energy and pressure, the range is the distance from the gun to the point where the photometer field of view intersects the beam axis. Pressure is changed, and another light curve is determined. Application of the longitudinal magnetic field does not significantly affect the extrapolated end point. The results obtained employing this technique are reproducible between the bell jar and the large vacuum chamber and are shown in the curve (B) of Fig. 12, which should be considered the most reliable optical range curve. The points plotted in Fig. 12 were obtained by multiplying the experimental pressures by the ratio of the indicated experimental ranges to $3/4$ in. Visual estimates give longer ranges as shown by (D), rather as expected.

Two similar measurements were made, with the monochromator-detector as the photometer, to check the sphere results at two specific bands, the 3914-Å first negative and the 10,510-Å first positive bands. To obtain sufficient light, the slits were opened to 1 cm. The straight-line portion of the cutoff curve was rather short for the 10,510-Å band, but the results indicated that the critical voltage for this band was from 5 to 10% lower than that for the 3914-Å band, which points to a somewhat longer range for the excitation of the first positive radiation.

Range Measurements with a Movable Probe

Other range measurements were made by moving a light and current detector along the axis of the glow, rather than moving the glow past a fixed detector. The arrangement will not be described in detail. Suffice it to say that the light probe is a narrow-field light collector looking out normal to the beam axis in all directions, with the light brought to an outside detector by a light pipe. The current probe is a multigrid protected Faraday cup. The cup is a hollow cone whose polished outside surface directs light down the light pipe as part of the light probe.

Measurements are in reasonable agreement with those of the fixed narrow field photometer, unless

the glow gets too far down the cylindrical vacuum chamber. The range measured is then much too short; it is not clear why.

The current probe was unsuccessful, or perhaps too successful. There are five grids in front of the cup. The first is grounded and part of the shield. The second, biased negatively, stops slow electron entry. The third, biased positively, stops positive ion entry. The fourth, biased negatively, repels secondary electrons or photoelectrons emitted from the collector cup. The fifth, at cup (ground) potential, shields the inside of the cup from the fields outside and is probably superfluous. With the grids biased in this way, the probe was intended to be sensitive only to high energy electrons, that is, to electrons with energy sufficient to pass the first grid. When the probe was moved through the glow, there was no characteristic break or identifying feature in the current vs distance plot to which to assign a range value. A semilog plot gave a very nice straight line. In retrospect, this perhaps should have been expected; at any given distance from the gun there are always a few high energy electrons which manage to reach that point without suffering the normal amount of energy loss, and their number decreases exponentially with distance. One could take the range as that distance through which the current falls by $1/e$, but this is not very useful.

ACKNOWLEDGMENTS

The writer is indebted to Cornell University for granting a sabbatical leave and to the Los Alamos Scientific Laboratory for making its facilities available to him. Special appreciation goes to Herman Hoerlin for extending the invitation to spend the year, for originally suggesting the experiment, and for continued support and encouragement. Others in Group J-10 at Los Alamos have been most helpful, but particular thanks goes to Redus Holland for his interest and his help in many discussions, in acquiring apparatus, and in preparing this report. Main and Division shop people lent much assistance. A great debt of gratitude is owed Casey Stevens, who worked faithfully with the writer in all phases of the endeavour--location and

setting up of equipment, data taking, operation and maintenance, design, shop fabrication of parts, and the like. Without his aid the year would not have been nearly so fruitful or so pleasant.

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