NEAR INFRARED SPECTRA FROM BEAM-FOIL-EXCITED ATOMS

by

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ABSTRACT

This thesis describes an attempt to extend the beam-foil technique into the near infrared ($1 - 2\mu$). Ionized beams of hydrogen, helium, neon, and boron, with particle energies between 0.15 and 1 MeV were produced by a Van de Graaff accelerator. The beam passed through a thin carbon foil which acted as an exciter. Subsequent de-excitation of the atoms provided the radiation source for this study. The beam radiation was analyzed with a grating spectrometer equipped with a visible light-blocking filter and a lead sulfide detector. A search was made for the strongest infrared lines in neutral hydrogen, helium, and neon. No emission lines were seen at the maximum sensitivity of the equipment used. Infrared radiation in the form of a continuum was observed from the exciter foil. From these experiments and theoretical calculations an upper limit to the power detectable from a beam-foil source in the near infrared has been set at 10^{-12} watts. The experimental parameters used in these experiments are provided as a guide for future studies in this area. Also suggestions for improvements in the detection system and experimental technique are included.

CHAPTER I

INTRODUCTION

Work in the infrared using the beam-foil method [Bashkin 1968] as a source began in August, 1969, when Dr. Basil Curnutte, from Kansas State University, visited the laboratory. Together we set up the first experiment in an attempt to detect infrared radiation. Results of this first search can be simply stated: no emission lines were seen from the hydrogen or neon beams which were investigated. A continuum in the infrared from the carbon exciter foil was observed, however, and a rough value for a temperature obtained from Wien's Law gives about $1200°K$ when a 1-MeV, 5 μA, H_3^+ beam goes through the foil. Since the relative sensitivity of the entire detection system as a function of wavelength is not well known, the temperature given is almost meaningless. For foil radiation measurements, the foils were placed at $45°$ to the beam, so that they could be viewed by a monochromator equipped with a lead sulfide (PbS) detector. The sensitivity of the detection system was usually not greater than 200 μV, which was the limit set by noise.

There are several reasons for extending studies of beam-foil spectra to the near infrared region. Probably the most important is to extend measurements of mean lives of excited states for which the beam-foil method is well suited. Infrared lifetime measurements can be used to check measurements made in the visible and ultraviolet. For example, the mean life of the 2 $^1P_0$ level in He I can be measured both by

observing the $2\,^1P_0 \rightarrow 1\,^1S_0$ transition in the u.v. (584.33Å) or the $2\,^1P_0 \rightarrow 2\,^1S_0$ in the i.r. (20,581Å). There are many instances where levels decay <u>only</u> with emission of photons in the i.r. The $2\,^3P_2^0$ level in He I is an example where the only allowed transition is $2\,^3P_2^0 \rightarrow 2\,^3S_2$, corresponding to 10,830Å.

In addition to theoretical interest in studies of this region, there is also a practical application in astrophysics. Presently there is a search for $\lambda 16,240.32$Å of Boron I in the sun. Although the mean life of the upper level has been measured from a transition in the u.v. [Martinson and Bickel 1970a], and theoretical calculations have been made for the oscillator strength of the infrared line [Weiss 1970], an experimental determination would prove valuable in determining the abundance of boron in the sun. Another reason for pursuing infrared beam-foil studies is to search for forbidden lines and other lines not seen in conventional light sources as has been done for the visible and ultraviolet [Berry et al. 1970]. For the above reasons, the work begun by Dr. Curnutte and myself was continued. The original goal of this study was to obtain and identify $1 - 2\mu$ infrared spectra from a beam-foil source, using standard infrared equipment and techniques. It was expected that mean-life measurements by other investigators would follow. Since no infrared emission lines were observed, however, this paper will report the nature of the attempt, and relevant data about the experimental conditions and equipment that was used. Suggestions are also listed which may be helpful in any extension of the experiments.

CHAPTER II

INSTRUMENTATION

The radiation source (beam, discharge tube, pyrometer, etc.) was modulated by a mechanical chopper. From three chopping rates available (13, 50, and 75 Hz), 75 Hz was selected and checked by a wave analyzer at the new University of Arizona Optical Sciences Infrared Standards Laboratory. The chopper also provided a reference signal to a lock-in amplifier which synchronously demodulated the detector output.

The position of the chopper with respect to the source and spectrometer was found to be critical. The best position was as close to the source and far from the entrance slit as possible, so that the chopper's aperture did not reduce the solid angle seen by the collector lens or cause excessive 60 Hz noise in the detection system. If the chopper was operated close to the spectrometer entrance slit, a grounded shield placed over the power cord reduced, but did not eliminate, the induced noise. A similar difficulty was encountered when alternating current operated a Geissler tube source. When the chopper was placed close to this source, the reference voltage and frequency became erratic. Suitable placement of the chopper eliminated these problems as did operation of the Geissler tubes on direct current.

After passing through the chopper, the radiation was collected by a 14 cm focal-length glass lens operated at f/3.4 and magnification one. The purpose of the lens was to collect a larger solid angle of the

source in order to fill the optics of the spectrometer. Since the spectrometer's effective f-numbers range from f/4.3 to f/5.2, the system was overfilled. The glass did not reduce the useful range of the spectrometer but did act as a long wavelength cut-off filter, since radiation above 2.7 μ was not transmitted. The lens was mounted in a cardboard tube which was bolted to the spectrometer housing. Therefore the lens and spectrometer could be treated as a unit.

A simple lens, such as the one used does not focus all wavelengths at the same point, but focuses the longer wavelengths farther than the shorter wavelengths. Since the optical system was most easily focused using visible light, and since perfect (aberration-free) imaging was not essential to the operation of the detector, if the infrared focal point was within the depth of field of the visible light focal point, then an extended source also had an acceptable focus in the infrared. The observed depth of field for the lens was 5 mm. To calculate the change in focal point from the visible to the infrared, the thin lens formula was used. Differentiating this formula [Longhurst 1968, p. 52] gives:

$$\Delta f = f_o \frac{\Delta n}{n-1}$$

where

Δf = change in focal point

f_o = focal length at λ_o

$\Delta n = n_o - n$

n_o = refractive index at λ_o

n = refractive index at λ

Using zinc crown for the glass composition, λ_o = 0.5889 μ, λ = 2 μ, n_o = 1.517, n = 1.497 [Weast 1964, p. 105], and f_o = 140 mm, we find Δf = 5.41 mm increase in focal length. Therefore, it was sufficient to use λ5461Å from mercury to focus the slit at the front of a 5 mm extended object (such as the beam) and make no further adjustments for observations in the infrared.

In order to separate second and higher-order visible radiation from the infrared, a No. 87 Kodak Wratten filter was used as an order sorter. The filter, mounted on a filter wheel supplied with the spectrometer, could be rotated out of the light path for observations in the visible. The transmission properties of the gelatin filter are given in Fig. 1. The experimental points correspond to the transmission of the prominent lines in mercury. The useful range of the spectrometer was 0.8 - 2.5 μ when the filter was used.

The spectrometer was a single pass Littrow mount Perkin-Elmer Model 210B equipped with 1440 ℓ/mm and 600 ℓ/mm gratings mounted back-to-back on a kinematic mount (see Fig. 2). Interchange between the two was made by a simple rotation of the grating mount. No effect of repeated interchange on the wavelength dial calibration was noticed. The 600 ℓ/mm grating, blazed at 1.6 μ with a range of 0.76 - 2.6 μ, was used for all visible and infrared observation. The 1440 ℓ/mm grating, blazed for the visible, was used for alignment, taking advantage of first-order radiation. A 45° mirror at the exit slit allowed two detectors to be placed on the spectrometer at one time. By manipulating the mirror from outside the spectrometer, one could switch from an externally mounted
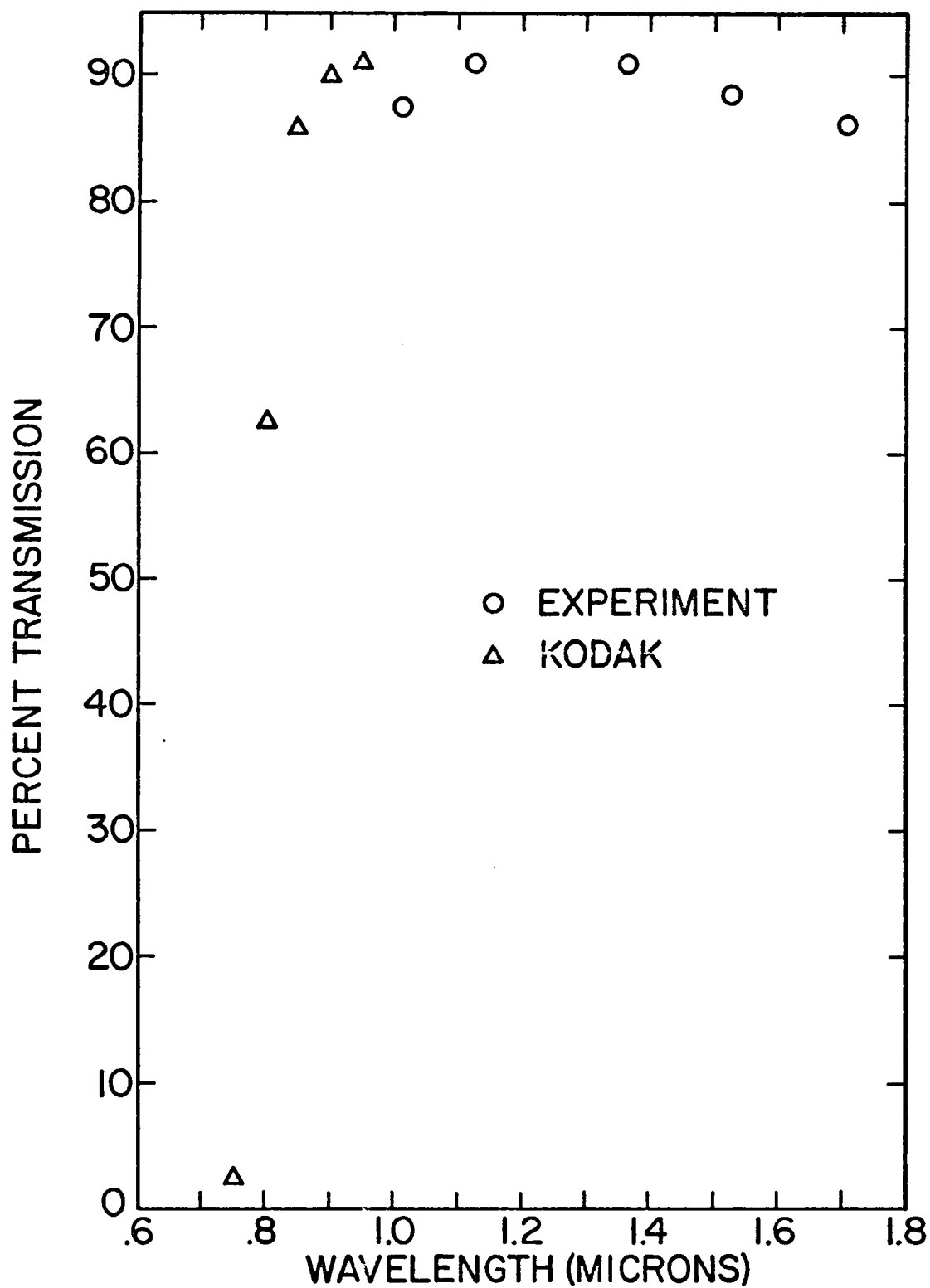
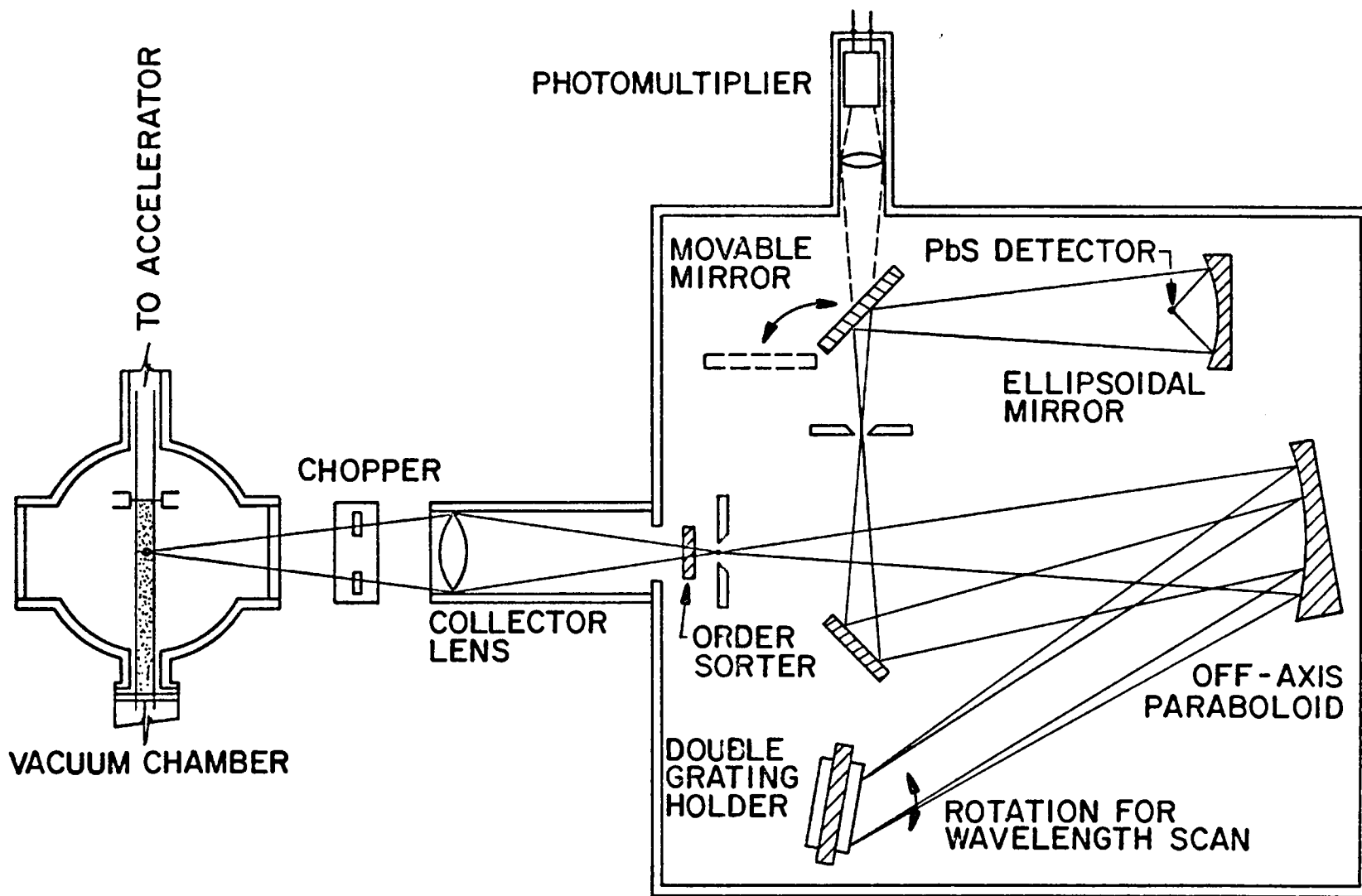Fig. 1.   PERCENT TRANSMISSION OF
KODAK #87 WRATTEN FILTER

Fig. 2. SCHEMATIC OPTICAL ARRANGEMENT

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photomultiplier to an internally mounted lead sulfide detector. Wavelength scans were made with a geared drive, linear in wave number, which was synchronized with a strip chart. Fiducial marks were placed on the strip chart every 40 cm^{-1} to help identify the spectra. The wavelength dial and reference marks were calibrated from the infrared spectrum of an iron-argon lamp to get a dial number versus wavelength graph. For this calibration, line identifications were made by comparing the observed lines with those in the literature [Rao, Humphreys, and Rank 1966]. It was immediately apparent that the excitation process is an important parameter in the production of spectral lines, i.e., the relative intensities of certain observed lines were quite different from those reported in the reference literature.

The accuracy of line identification for various slit widths was determined by using the lead sulfide detector and observing $\lambda 5461$Å of mercury in second order. The results are shown in Table I.

The theoretical first order resolving of the 600 ℓ/mm grating is 41,160. At 1.7 μ, 0.4Å could theoretically be resolved. Since resolution is also a function of slit width, an indication of the resolution at various slit widths was made using six mercury lines at 1.7 μ as shown in Fig. 3. Table II lists resolutions estimated from Fig. 3. For a given slit width, the resolution listed also depended on individual line intensities and time constants of the detector and recording equipment. The best resolution occurs for the slowest wavelength speed, and a chart speed which produces symmetric triangular lines.

The entire optical system consisted of a quartz window on the beam-foil chamber, a glass collector lens, an order-sorting filter, and

Table I. Accuracy in wavelength determination as a function of slit
width.

Slit width (mm)	Dial Deviation 1	Wavelength error (Å)
0.20	+ 0.005	+ 2
0.50	+ 0.013	+ 4
1.00	+ 0.030	+ 7
1.50	+ 0.025	+ 6
2.00	+ 0.060	+ 14

Table II. Resolution at 1.7 μ as a function of slit width.

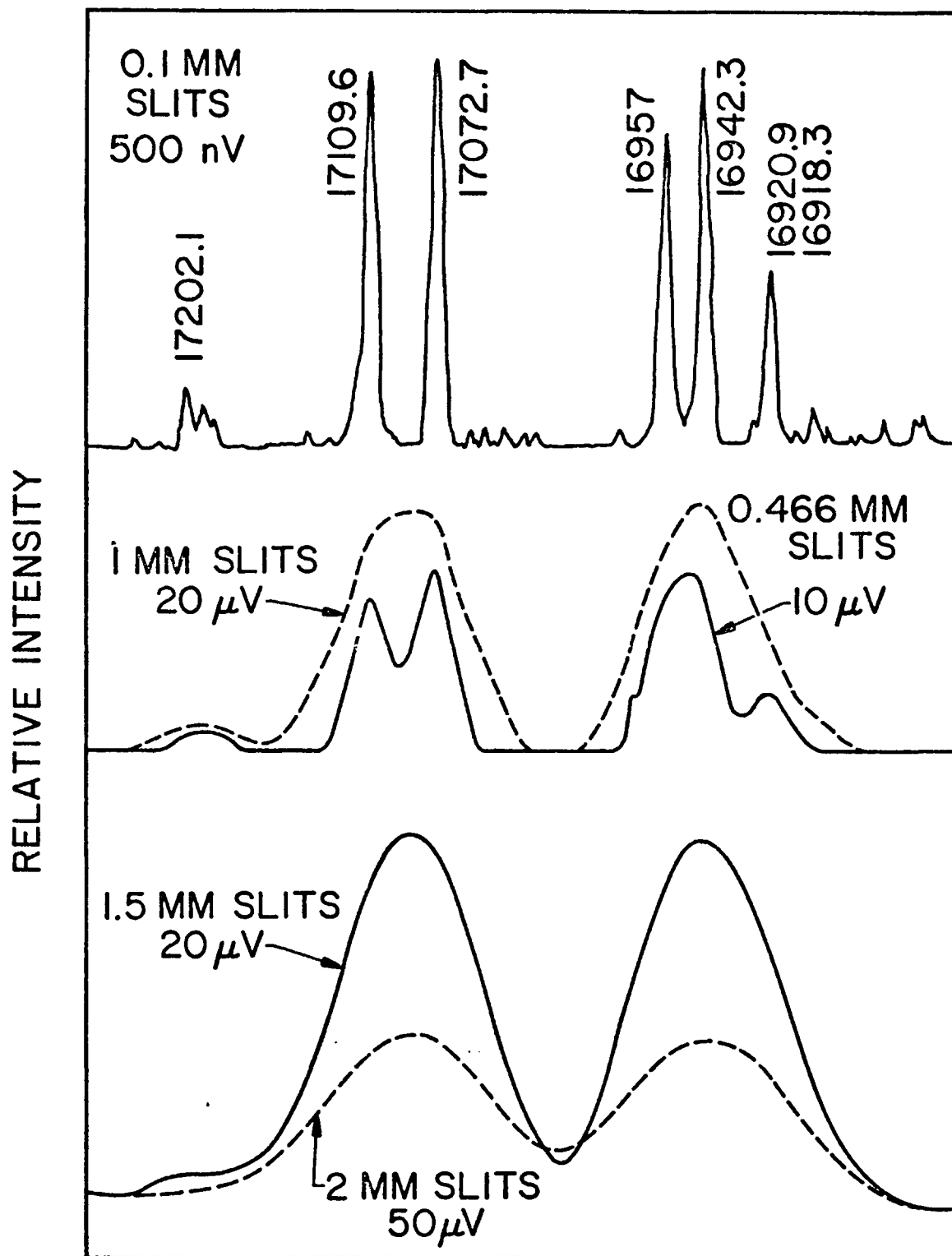| Slit width (mm)	Resolution (Å)
0.100	> 2
0.466	< 22
1.000	> 38
1.500	100
2.000	> 100

Fig. 3. RESOLUTION AS A FUNCTION OF SLIT WIDTH

the spectrometer grating and mirrors. An estimate of the transmission of the entire system to each detector can be made from the values given in Table III. The experimentally-determined infrared transmissions were found by placing the element in question in the beam path of the spectrometer using the prominent mercury lines as sources, and measuring the decrease in signal. An average transmission for the 1 - 2μ region is quoted. In the case of the glass lens, a quarter-inch plate was used for the test. The collector lens and spectrometer were constants for the measurements which were made in air. Because there are six reflections in the spectrometer when the lead sulfide detector is used, the total transmittance is 27 ± 10%. For the photomultiplier there are two fewer reflections, no filter is used, the grating is used in second order, and there is a quartz lens in the detector mount to image the slit onto the photocathode. Taking these changes into account, the transmittance to the photomultiplier is 30 ± 10%. The error has to be estimated to take into account differences in the optical surfaces actually used and the values quoted in the literature. In addition to the absorption by the optical elements, atmospheric absorption at 1.4μ was observed. To decrease atmospheric absorption, the light path was frequently purged with nitrogen.

Two types of detectors were used with the spectrometer. Photomultipliers were mounted outside the spectrometer housing. The photomultipliers were used to check the optical alignment, detect and identify well-known beam-foil lines, and allow a comparison of the lead sulfide and photomultipliers to be made. An EMI D224A with a spectral response of 3700 - 8000Å, and an EMI 9502S with a spectral response of

Table III. Transmissions of the optical components.

Element	Transmission or Reflection (%)	Remarks
quartz window	88	1 - 2 μ experiment
	95	5000Å[a]
collector lens	70	1 - 2 μ experiment
	90	5000Å[a]
filter	85	1 - 2 μ (see Fig. 1)
		used for i.r. only
grating	70	first order
	56	second order
		(measured with respect to a mirror)[b]
mirrors	95	1 - 2 μ[c]
	90	5000Å[a]

[a]Hudson 1969, p. 221.

[b]Spex Speaker 1965, p. 3.

[c]Hudson 1969, p. 354.

of 3000 - 6000Å were operated at -1500 volts d.c. The output of the EMI D224A went to a lock-in amplifier and was displayed on a strip chart. The output of the EMI 9502S went to an Ortec Low Noise Preamp (Model 101) and an Ortec Low Noise Amplifier (Model 201). The amplifier output went to an Intertechnique Didac 4000 multiscaler.

The infrared sensitive lead sulfide detector was mounted inside the spectrometer housing. Originally, the output of the detector went to a copy of a Perkin-Elmer preamp (part no. 112-0028) mounted inside the spectrometer base with the power provided by a Perkin-Elmer Amplifier (Model 107). The preamp output went to a Princeton Applied Research lock-in amplifier (Model HR-8) and was recorded on a strip chart. The sensitivity, however, was limited by excessive noise which was shown by an oscilloscope to be 60 Hz signals in the preamp. The preamp was therefore abandoned in favor of a more basic bridge technique for detecting changes in the resistance of the PbS cell due to incident radiation. A Leeds and Northrop Wheatstone Bridge was used with the detector occupying the position of the unknown resistance. An 8.4 volt battery provided the bridge-operating voltage. The commercial bridge permitted the circuit to be nulled before each use to three significant figures with a galvanometer. Slight drifts in the null were noted over long periods of time (hours) but these drifts did not interfere with the operation of the detector even though the null condition is very sensitive to resistance change.

The detector resistance depended on bias polarity. For example, the zero bias resistance of 5×10^6 ohms was preserved for one polarity,

but increased to 8×10^6 ohms for the opposite. Although the sensitivity of the detector increased with the increasing resistance, the noise output similarly increased. The lower resistance polarity was therefore used for all measurements. The bridge output was connected directly to the lock-in amplifier operated in the differential mode. Differences in the two sides of the bridge were thereby amplified in phase with the modulated radiation. The twin shielded cable which carried the detector output was grounded only at the bridge to discourage ground loop currents. The system picked up very little noise as long as power cables were kept away from the bridge battery. Although the spectrometer's motorized wavelength drive added noise to the system, it did so at a tolerable level.

The noise output from the amplifier could be reduced by adjusting the preamp AC balance and increasing the Q value. An oscilloscope is a valuable aid for evaluating and reducing noise. On a strip chart, noise appeared as random fluctuations dependent on the time constant and roll-off rate (amount of signal filtering) in addition to those parameters previously discussed. A 12 db/octave roll-off rate and 300 msec - one sec time constants kept noise excursions to a minimum without significantly suppressing the signal. With the above-mentioned improvements in circuitry, the sensitivity improved by a factor of 400. The specifications and operating parameters for the PbS detection system are listed in Appendix A.

From the Specification Clarification for the PAR lock-in amplifier, a calculation of the minimum detectable signal of 32.6 nV was made.

This calculation appears in Appendix B. In practice, the minimum detectable signal was found to be 100 nV and was noise limited. If a room temperature spectral response (R_λ, volts/watt) of 10^4 volts/watt is assumed for the PbS cell (there is disagreement in the literature about this figure; values are quoted from 4×10^3 to 10^6), then the amplifier limited minimum detectable power is 3.26×10^{-12} watts, or about 2×10^7 photons/sec at λ 1.5 μ incident on the detector. Using 30% for the transmittance of the optics and 0.068 sr for the lens solid acceptance angle (Appendix A), one finds approximately 10^{10} photons/sec radiated in all directions are required to produce this minimum signal.

A detector limited minimum detectable power or noise equivalent power (NEP) can be calculated from the spectral sensitivity (D^*, cm $\sqrt{\overline{Hz}}$/watt) if it is known for a particular detector. At 75 Hz, a typical D^* is 8×10^{10} cm $\sqrt{\overline{Hz}}$/watt [Hudson 1969, p. 365]. The calculation in Appendix C shows that the NEP is 5.1×10^{-13} watts or about 4×10^6 photons/sec at λ 1.5μ incident on the detector. Assuming the same spectral responsivity as used above, 5.1×10^{-9} volts is the detector limited signal. Therefore the detection system was theoretically amplifier limited to about 3×10^{-12} watts at the detector or 10^{10} photons/sec (1.5μ) radiated by the beam. In practice one must bear in mind the noise voltage of the PbS detector itself was of the order of 10^{-6} volts. Therefore the ability of the amplifier to extract a signal buried in the detector noise sets a practical limit to the minimum detectable power somewhat above the calculated values.

Detector characteristics such as D^*, R_λ, the time constant, the optimum modulation frequency, and the optimum bias can be experimentally

determined with a 500°K blackbody and a variable speed chopper used in conjunction with standard test equipment [Hudson 1969, Chapt. 9]. Since the blackbody and chopper were not available in the laboratory, two tests indicative of the entire detection system's sensitivity were made. (The University of Arizona Optical Sciences Infrared Standards Laboratory has offered to calibrate our PbS detector when they become operational).

A GE30AT24 Ribbon Filament Pyrometer (#431-P-576, traceable to the National Bureau of Standards) operated at 1850°K (22.7 amps d.c.) provided the spectral sensitivity curve for the entire detection system. This curve is shown in Fig. 4, along with the curve for an 1850°K blackbody. No attempt has been made to correct the blackbody curve for the emissivity of the tungsten filament. The dip in the experimental curve at 1.17μ is believed to be a property of the grating. A similar dip has been noted for a 600 ℓ/mm 1.6μ blazed grating at The University of Arizona Lunar and Planetary Laboratory [Fink 1970].

A comparison of PbS and photomultiplier sensitivities is shown in Fig. 5. In each case 2 mm slits were used. A sensitivity of 10 mV was required for the photomultiplier while 10 μV sensitivity was used for the PbS detector. The output signals from both detectors were processed by the same electronics. The apparent factor of 1000 difference in sensitivity must take into account the decrease of PbS sensitivity in the visible region of the spectrum.

A standard test for the alignment and sensitivity of the PbS detection was devised in conjunction with the alignment of the ellipsoidal
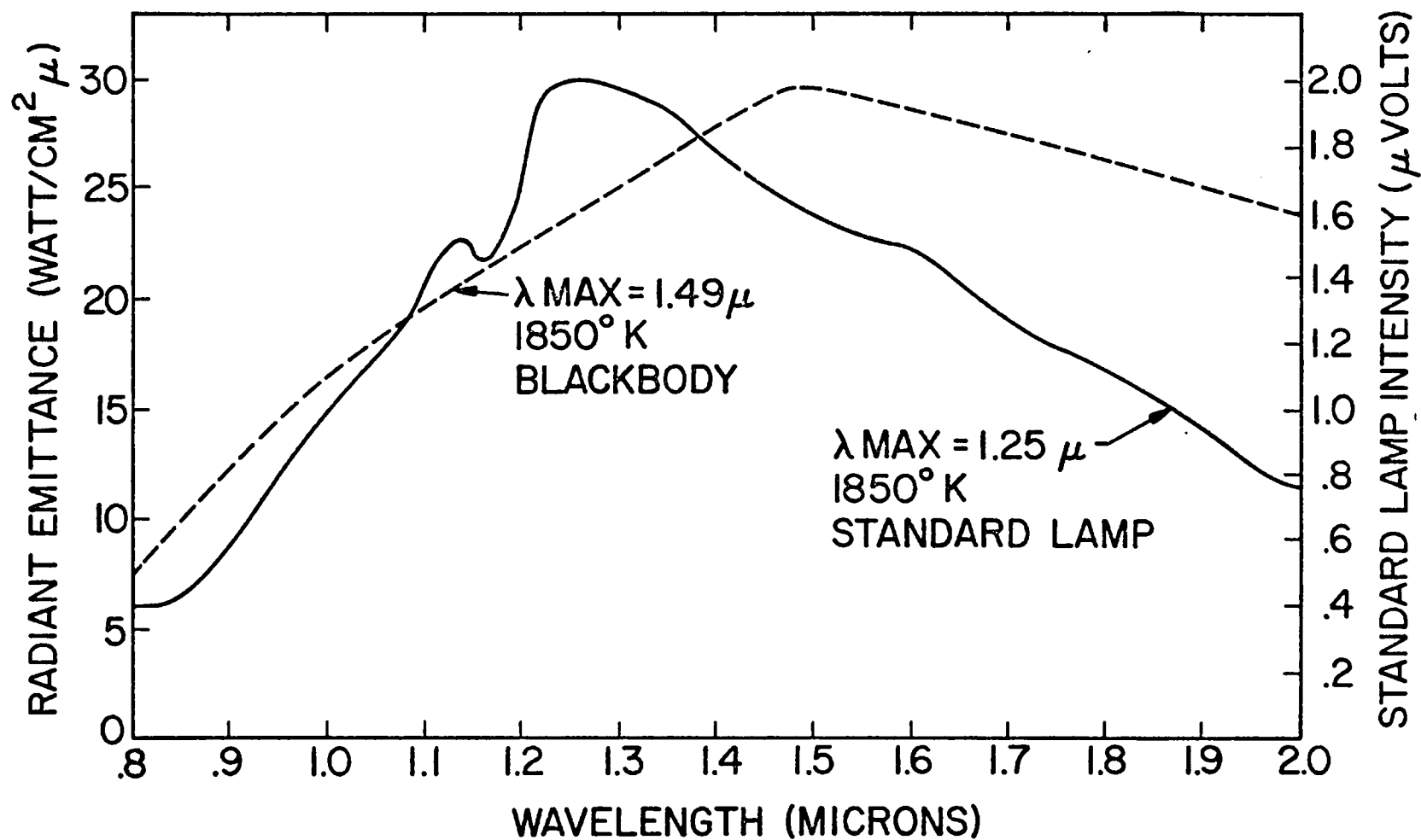
Fig. 4. SPECTRAL RESPONSE OF THE Pb S DETECTION SYSTEM
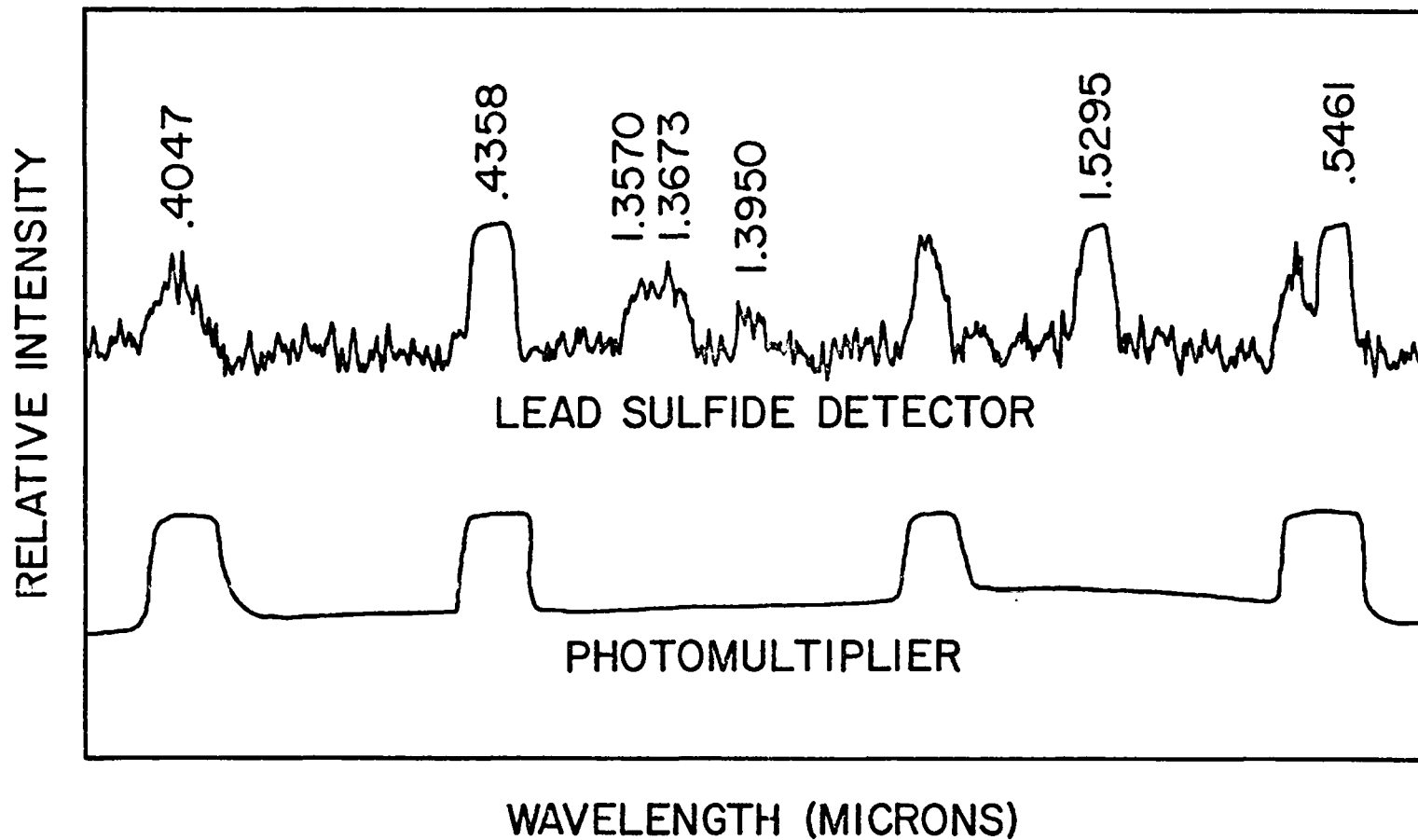
λ MAX = 1.49 μ
1850° K
BLACKBODY

λ MAX = 1.25 μ
1850° K
STANDARD LAMP

Fig. 5.   LEAD SULFIDE – PHOTOMULTIPLIER
SENSITIVITY COMPARISON

mirror in front of the detector. The relevant parameters for this test appear in Appendix D.

CHAPTER III

EXPERIMENTS

Three experiments are described in this section. Two involve carbon foil radiation which was observed in the early work. The third describes observation of beam-foil radiation.

The first carbon foil radiation observations were made with apparatus similar to that shown in Fig. 2 with the exception that filters and photomultipliers were not used. Signal processing was done as described in the Instrumentation chapter before the preamp was replaced. The carbon foils were excited by hydrogen and neon beams with energies between 0.150 and 1 MeV, produced by a Van de Graaff accelerator. The target chamber was evacuated to 10^{-6} torr. Carbon foils at $45°$ to the beam were viewed directly with slit widths ranging from 2 mm to 0.5 mm. Currents varied from less than 1 μamp to 18 μamps.

A portion of the radiation continuum observed with 0.5 mm slits from a carbon foil interacting with 150 keV H_3^+ particles is shown in Fig. 6. A dependence of intensity on beam current is immediately apparent from the two curves. The total extent of the radiation is not known since the spectrometer could not scan above 2.6μ, however, the short wavelength end was observed to be 1.6μ. The detail in the two curves beyond 2.55μ was shown by subsequent observations to be a coincidence. The reason for the dip at 2.2μ is not known. The detection system does not exhibit this dip in the optical pyrometer (standard lamp) spectrum.
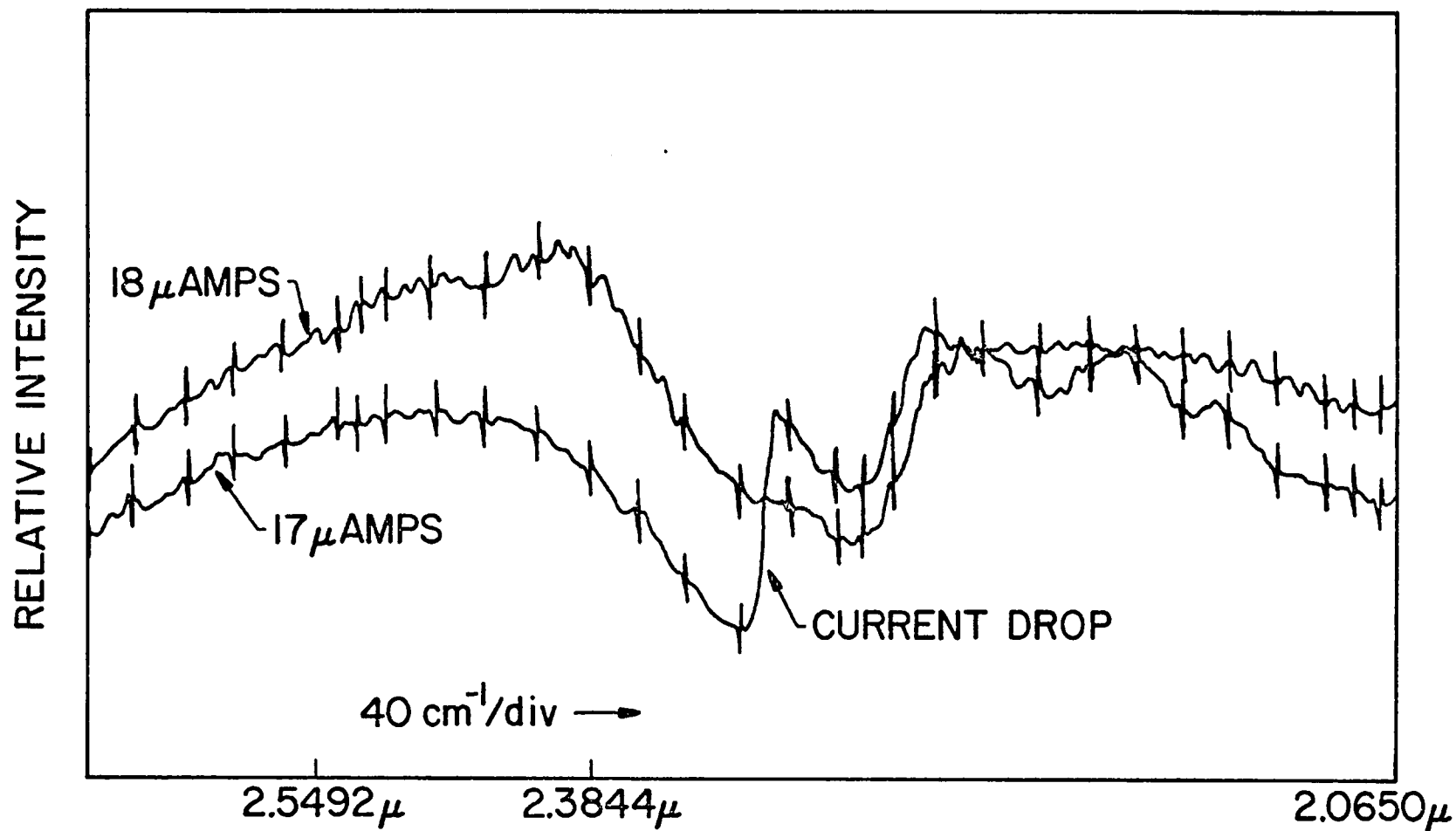
RELATIVE INTENSITY

18 μAMPS

17 μAMPS

CURRENT DROP

40 cm⁻¹/div ⟶

2.5492μ   2.3844μ   2.0650μ

Fig. 6.   CARBON FOIL RADIATION

Figure 4 shows this spectrum out to 2μ, however, the experimental curve continued to 2.6μ without the appearance of the dip.

No emission lines were detected from either element used. The foil radiation was not of major concern so that further studies of it were not made.

To avoid foil radiation and increase the amount of radiation reaching the detector, the spectrometer was removed from the optical system. A red glass filter to cut off radiation below 6000Å was the only optical element other than the collecting lens. With experimental conditions as before, hydrogen, boron, and neon beams were passed through carbon foils (in the normal position). By moving the foil holder, the beam could be viewed from 6 cm downstream from the foil to 1 cm upstream from the foil. The beam could be quickly removed from the chamber by closing the chamber-beam pipe valve. A dependence of the radiation observed on beam current and foil distance was established. Although different energies were used and no energy dependence was noted, the possibility of an energy dependence is not ruled out. The variation of intensity with distance from the foil appeared to follow an inverse square law rather than the exponential decay expected of moving radiators. However, such an exponential decay could not reasonably be expected to predominate when all wavelengths are observed at once. The current appeared to be the most important parameter for the radiation observed. For currents less than a microamp, radiation was usually not observed. The decay time (peak-to-zero intensity) of the radiation when the beam was removed from the chamber was the most important indication

of the nature of the radiation. If the radiation entering the spectro-
meter was stopped by means of a shutter in the light path, a decay time
of six seconds was measured. It should be noted that the rise time is
half this value. Presumably the decay time is larger because of signal-
generated noise in the detector. However, removing the beam from the
chamber increased the decay time by a factor of ten as shown in Fig. 7.
This significantly longer decay time showed foil radiation to dominate
even at 6 cm from the foil as in the case of Fig. 7. In most cases, no
visible glowing of the foil was seen with the unaided eye. The larger
fluctuations observed when the beam is present are due to beam fluctua-
tions. Six per cent beam current fluctuations were common. Care was
taken to shield the foil from view in subsequent experiments.

The inability to observe beam oriented radiation was not consid-
ered proof that none was observable since improvements in the electron-
ics had not yet been made.

The experimental arrangement for the beam-foil studies is shown
in Fig. 2. The beam-foil chamber was evacuated to 2×10^{-5} torr. A ro-
tating foil wheel allowed changing the 10 - 100 μ gm/cm^2 carbon exciter
foils as they broke. A Faraday cup monitored the beam current. The
viewing window was quartz and the opposite window was plexiglas. The
latter window allowed the introduction of a test spectrum into the spec-
trometer while the chamber was in use. Beams used were produced by a
Van de Graaff accelerator and mass analyzed by a magnet before entering
the chamber. Further identification of the beam was made from the visi-
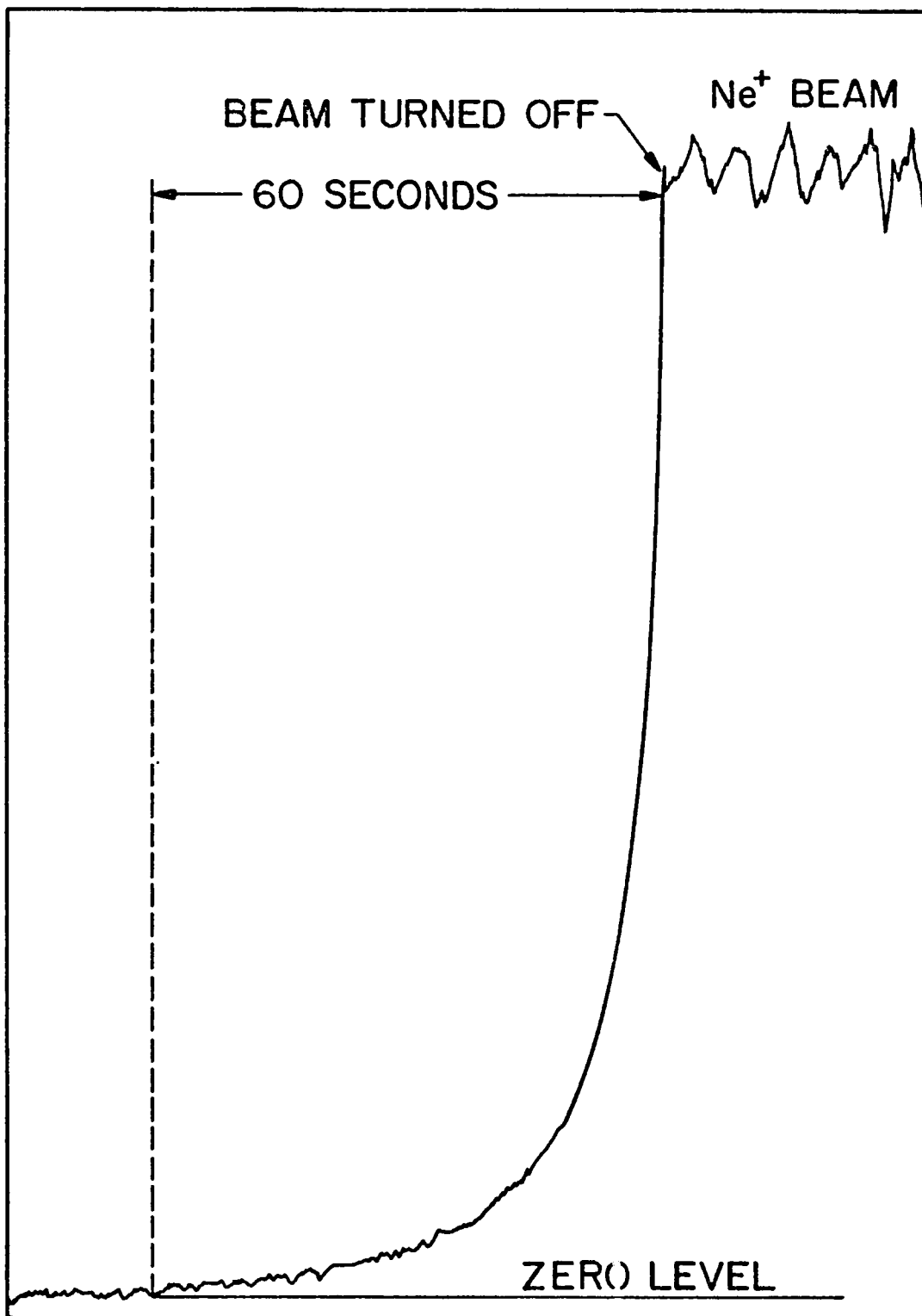ble spectrum of the radiation beyond the foil.

Fig. 7. CARBON FOIL RADIATION DECAY

The alignment procedure for the spectrometer with respect to the beam and target chamber will be described here. Before evacuation of the target chamber, the quartz window was removed to permit access to the foil wheel. The photomultiplier assembly was removed and a mercury lamp put in its place. A ronchi ruling was placed at the exit slit so that the image of the entrance slit could easily be focused in the target chamber onto a tube of white paper the size and shape of the beam, which was placed in the foil holder. The slit image was focused on the leading edge of the tube to insure the proper focus of the infrared radiation as explained in the Instrumentation section. To insure proper operation of the detector at this point, a mercury lamp replaced the paper target and the detector was tested according to the procedure in Appendix D. The lamp was then placed behind the plexiglas window and the new peak signal was used to check the alignment and operation of the entire system during beam-foil observations.

The intensity of the beam-foil source at a distance x downstream from the exciter foil is proportional to exp $(-x/\tau v)$ [Bickel 1967], where τ is the mean life in seconds of the excited level of the atom under study, and v is the velocity in cm/sec of the emitting atom. For mean lives of the order of 10^{-8} sec and velocities of the order of 10^8 cm/sec, the intensity is proportional to exp $(-x)$. The distance $x = 0.5$ cm was chosen as the position far enough from the beam to avoid foil radiation, yet close enough to obtain a large amount of beam radiation. Since the magnification of the collector lens was 1, the area of the beam viewed at $x = 0.5$ cm was equal to the slit width used.

Figure 8 shows the results of accelerating He$^+$ to 175 keV and observing the beam with an EMI 9502S photomultiplier with a multiscaler read-out. A 1.8 µamp beam entered the chamber. Six lines in the visible spectrum of helium were observed with 2 mm slits. The PbS detector recorded no radiation either in the visible or infrared region of the spectrum. A maximum sensitivity of 100 nV was used and the system was checked with the mercury test lamp during the experiment. Slow scans for eight known infrared helium lines were made without result. The helium photomultiplier results were repeated with a 2.5 µamp beam. Another search for the known helium i.r. lines revealed nothing.

An attempt to detect radiation from 175 keV hydrogen failed even though H_β and H_γ were observed with the photomultiplier. Although a visible beam could be seen with the unaided but dark-adapted eye, H_α was not detected with the PbS detector. A search for members of the Paschen series also yielded no results.

The inability to see hydrogen or helium spectra in the infrared region places a limit to the detection capabilities of the system used. The ability to detect the visible spectrum with a photomultiplier demonstrates the ability of the optical system to do beam-foil work. The brief studies of the carbon foil radiation have raised questions which may be of interest to investigators of the beam-foil interaction.

RELATIVE INTENSITY

3203, 3211 He II (4th ORDER)

4471
(3rd ORDER)

4686 He II, 4713
(3rd ORDER)

4921
5015 (3rd ORDER)

3889 (4th ORDER)

Fig. 8. HELIUM BEAM-FOIL SPECTRUM
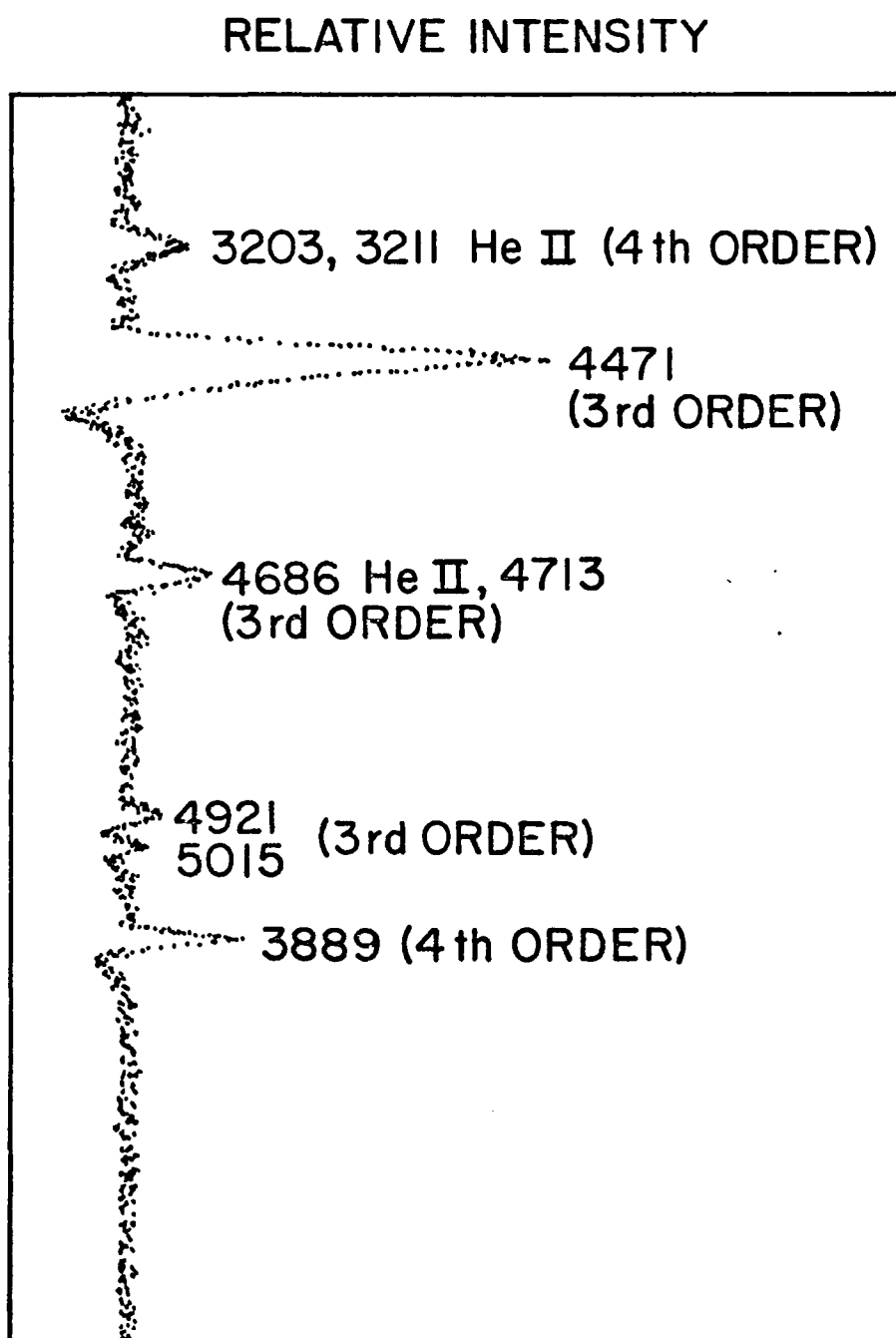
CHAPTER IV

CONCLUSION

The capability of the present i.r. detection system to do tradi-
tional infrared spectroscopy has been demonstrated. This section will
evaluate the extension of the beam-foil method into the near infrared.

In the experiments, an attempt to detect Paschen α ($\lambda 1.8751$ μ)
in hydrogen (n = 4 to 3) failed. The inability to detect this poten-
tially strongest line places a limit on the detectable power from any
single line from a beam-foil source. In the experiment, 6 μamps of 175
keV H_3^+ were used. An estimate of 10^7 excitations of the 4P level in
H I per μamp beam per second has been made from Lyman γ (n = 4 to 1)
measurements [Andrä 1970]. Using this number, the initial number of
atoms/cm^3 in the 4P level (N_{4P}) is obtained. Note, however, that only
two of the five transitions which compose Paschen α arise from the 4P
level. The power detected from Paschen α at a distance x cm from the
foil is given by

$$I(x) = k\ N_{4P}\ (A_{4P3S} + A_{4P3D})\ \frac{hc}{\lambda}\ \frac{2av}{\alpha_{4P}}\ \exp\ (-\alpha_{4P}\ \frac{x}{v})\ \sinh\ \frac{\alpha_{4P}{}^{\delta}}{v}$$

[Bickel 1967]

where k is the total efficiency of the optical system and detector,
($A_{4P3S} + A_{4P3D}$) is the total transition probability for the two transi-
tions under study, λ is the wavelength of the radiation, α_{4P} is the sum

of the transition probabilities of all transitions from the 4P level (see Fig. 9), v is the velocity of the beam in cm/sec, δ is half the length of the beam viewed by the spectrometer, and a is the cross sectional area of the beam. The details of the calculation are in Appendix E, which shows 3.58×10^{-17} watts or 330 photons/sec would theoretically be detected. Although only two of the transitions responsible for producing Paschen α were used for this calculation, the value quoted should be close to the true value since S and P levels have been observed to be overpopulated at low energies in the beam-foil excitation process [Yager 1969]. From the calculated detector limited minimum detectable power of 5×10^{-13} watts (Appendix C), it is obvious that Paschen α is beyond the range of detection.

In recent years several methods of increasing the detectivity of a detector have become available. Among these are the use of cooled wide band filters and cooled apertures for the reduction of background radiation incident on the detector, and cooling the detector to decrease detector noise. External noise pickup has been reduced by cooling the detector preamp as well. At best, such techniques provide an additional order of magnitude in detectivity. State-of-the-art PbS detectors now have an NEP of 10^{-14} watts [Martin 1966, p. 26; Brancazia and Cameron 1968, p. 45]. These detectors are clearly not good enough for the low levels of power encountered. Only single photon counting devices would be of value here and none are presently available for wavelengths longer than 1.3μ.

Another estimate of the potential of the beam-foil source for i.r. studies can be made from an estimate of the beam current needed to
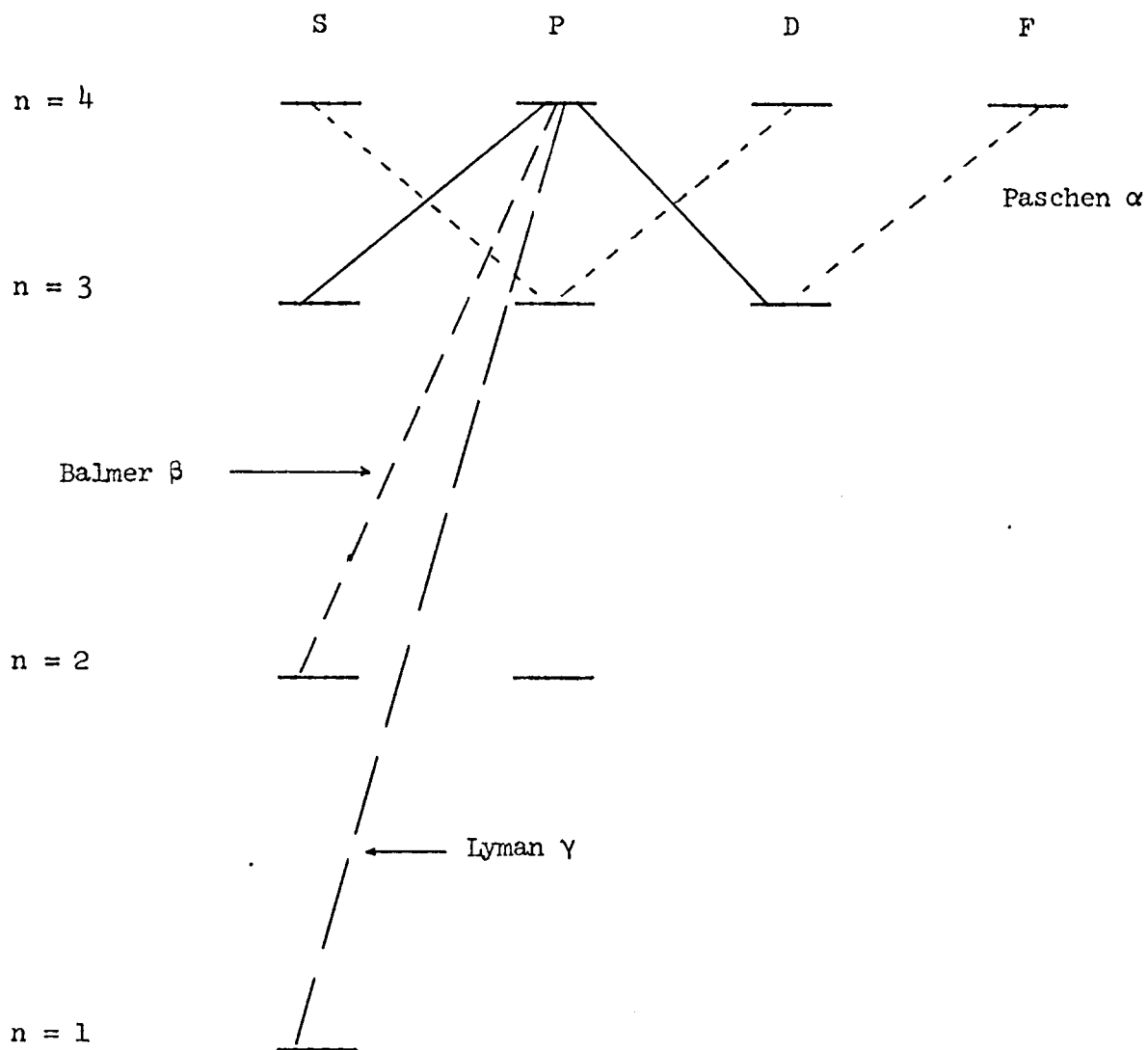
Fig. 9. Partial Hydrogen Energy Level Diagram.

just detect λ 1.083 μ (2 $^3P_1$ → 1 $^3S_1$) in He I, using a detector with an

NEP of 10^{-14} watts. The experimental parameters are assumed the same as

in the case of hydrogen except that 300 keV energy is used. In this

case the intensity is known and the number of particles/cm^3 in the 2 $^3P_1$

level is to be found and converted into a beam current. The calculation

in Appendix F shows a 5.2 x 10^{-3} μamp beam is needed if one assumes 20%

of the original He$^+$ beam was excited into the 2 $^3P_1$ level after passing

through the foil. This is definitely not the case, so that the actual

current needed may be many orders of magnitude higher.

In the case of λ 1.083 μ is He I, there is a possibility of in-

creasing the beam currents used (2.5 μamps is common). In addition, an

optical system using fewer elements could be used to increase the amount

of radiation reaching the detector. A vacuum instrument, with the grat-

ing as the only element, connected directly to the target chamber could

increase the radiation at the detector by 30%. A by-product of an all

vacuum system is the elimination of atmospheric absorption. To increase

the radiation entering the spectrometer slit by a factor of 2, a focus-

ing mirror could be placed opposite the slit to double the solid angle

of the beam seen by the spectrometer. With these changes, it may be

possible to detect λ 1.083 μ with a state-of-the-art PbS detector. How-

ever, a photomultiplier with an S-1 response should be able to detect

this line with the present apparatus.

From the above calculations, the maximum power radiated by the

beam-foil source but not detected by the system used is the amplifier

limited power of 3.3 x 10^{-12} watts. The Paschen α calculation also

shows that this value could be as much as 5 orders of magnitude too

high.   Until the detectivity of the PbS cell used is known, a better

estimate of the magnitude of beam-foil i.r. radiation can not be made.

APPENDIX A

INFRARED INSTRUMENTATION

Signal Modulator:

Princeton Applied Research Mechanical Light Chopper Model BZ-1,
Serial 298, two blades, 75 Hz.

Signal Processing:

Princeton Applied Research Precision Lock-in Amplifier Model
HR-8, Serial 1291; Preamp Type A operated in the differential
(A-B) mode; selective external reference mode with reference
frequency and reference attenuation operated for 2 volt refer-
ence signal; 300 msec or 1 sec time constant at 12 db/octave
roll-off rate; phase and frequency trim operated for peak signal;
signal Q 10-25 for least noise interference; maximum sensitivity
200 nV (noise limited).

Signal Monitor:

Tektronix oscilloscope #551.

Collection Optics:

f/3, 14 cm focal length glass lens operated at f/3.4 and magni-
fication one; 0.068 sr solid acceptance angle.

Order Sorter:

No. 87 Kodak Wratten Filter, gelatin.

Spectrometer:

> Perkin-Elmer Model 210B; 600 ℓ/mm grating blazed at 1.6μ; 30-50
> Å/mm dispersion; linear wavenumber drive (400 cm^{-1}/turn).

Detector:

> Perkin-Elmer Kodak lead sulfide photoconductor in Perkin-Elmer
> standard thermopile holder operated as one leg of a Leeds and
> Northrop #4735 Wheatstone Bridge; 8.4 volt d.c. bias voltage
> across bridge;
>
> $D^* = 10^{11}$ cm $\sqrt{Hz}$/watt,
>
> 90° angle of view,
>
> 2 x 0.2 mm element,
>
> Room temperature operation,
>
> $R_\lambda \cong 10^4$ volts/watt,
>
> Dark resistance 5 x 10^6 ohms,
>
> Noise voltage 6 x 10^{-7} volts,
>
> Wavelength region 0.4 - 2.7μ.

Auxiliary Equipment:

> Leeds and Northrop #2435-C galvanometer to null bridge;
> 0.025μ amp/mm sensitivity.

APPENDIX B

AMPLIFIER LIMITED MINIMUM DETECTABLE SIGNAL

The amplifier is limited by Johnson Noise. The minimum detectable signal = Johnson Noise x $\sqrt{\text{Band width}}$ x Johnson Noise Voltage Multiplier. The PAR Johnson Noise versus source resistance curve gives the Johnson Noise for 88×10^3 ohms bridge resistance as 50 nV/$\sqrt{\text{Hz}}$.

The band width is given by 1/8RC for a 12 db/octave roll-off rate. 300 millisecond time constant gives 0.416 Hz.

The Johnson Noise Multiplier is $10^{F/20}$ where F is the noise figure in db given by the PAR noise figure contour. The contour for single ended operation can be used for double ended operation when the source is above 3×10^3 ohm resistance. This is satisfied by the bridge. The noise figure for 75 Hz modulation frequency and 88×10^3 ohm source resistance is 1 db.

Therefore the minimum detectable signal is

$$(50) \sqrt{0.416} \ 10^{1/20} = 32.6 \text{ nV.}$$

This occurs with a signal-to-noise ratio of one.

APPENDIX C

DETECTOR LIMITED MINIMUM DETECTABLE POWER

$$D^*_{max} = \frac{\sqrt{A\Delta f}}{NEP}$$

D^*_{max} = maximum spectral sensitivity $\frac{cm\sqrt{Hz}}{watt}$

A = detector area cm^2

Δf = amplifier band width Hz

NEP = noise equivalent power or minimum detectable power (watts) for a signal-to-noise ratio of one

We wish to know the NEP:

$$NEP = \frac{\sqrt{A\Delta f}}{D^*_{max}}$$

$D^*_{max} \cong 8 \times 10^{10}$ cm $\sqrt{Hz}$/watt at 75 Hz modulation frequency for an average detector.

A = 0.2 x 0.02 cm^2 from Appendix A.

Δf = 0.416 Hz from Appendix B.

The NEP is found to be 5.1 x 10^{-13} watts.

APPENDIX D

PbS DETECTION SYSTEM TEST PARAMETERS

1. Mercury pen-ray lamp positioned 25.5 cm from the collector lens, modulated at 75 Hz.

2. Slit width 0.466 mm.

3. No. 87 Kodak Wratten filter rotated into the light path.

4. 600 ℓ/mm grating set for $\lambda 10139 \text{Å}$ or 16.6 ± 0.02 dial numbers.

5. Exit mirror in position for PbS detector.

6. 200 μV sensitivity, 300 msec time constant, 12 db/oct roll-off rate.

7. Adjust phase, frequency trim, wavelength dial and lamp position for a maximum signal of 105 μV.

APPENDIX E

POWER DELIVERED TO THE DETECTOR BY PASCHEN α

The power detected at a distance x cm from the foil is given by

$$I(x) = k \, N_{4P} \, (A_{4P3S} + A_{4P3D}) \, \frac{hc}{\lambda} \, \frac{2av}{\alpha} \, \exp \, (-\alpha_{4P} \, \frac{x}{v}) \, \sinh \frac{\alpha_{4P}\delta}{v} \, .$$ The Con-

clusion contains an explanation of the individual terms. The values of

the terms are presented here.

$$k = \frac{\text{collector lens solid angle}}{4\pi} \times \text{detector efficiency} \times \text{optical efficiency}$$

Using the value in Appendix A for the collector lens solid angle, 0.5

for the detector efficiency [Hall 1970], and 0.3 for the optical effi-

ciency (see the Instrumentation chapter), we obtain

$$k = 6.33 \times 10^{-4} \, .$$

N_{4P} = number of atoms in the 4P level per μamp beam current per second x

beam current $\div$ volume of the beam after one second (measured from the

foil where volume is zero and t = 0). 10^7 4P atoms/μamp sec is ob-

tained from experiment [Andrä 1970], and 6 μamp H_3^+ beam was used. The

volume of the beam after one second is given by the length of the beam

after one second times the cross sectional area of the beam (a cm^2).

The velocity of the beam at 175 keV is 3.34 x 10^8 cm/sec. Using

a = 0.196 cm^2, we get

$$N_{4P} = 0.928 \text{ 4P atoms/cm}^3 \, .$$

The transition probability for the two transitions studied is

$$A_{4P3S3D} = A_{4P3S} + A_{4P3D} = 3.3 \times 10^7/sec \quad \text{[Bethe and Salpeter 1957]}$$

For $\lambda = 1.8751 \mu$, we find

$$\frac{hc}{\lambda} = 1.06 \times 10^{-19} \text{ joules}$$

$$\alpha_{4P} = A_{4P3D} + A_{4P3S} + A_{4P2S} + A_{4P1S} = 8.08 \times 10^7/sec \quad \text{[Bethe and Salpeter 1957]}$$

Using $x = 0.5$ cm, $\delta = 0.1$ cm, and $a = 0.196$ cm^2, we find

$$\frac{2av}{\alpha} = 0.81 \text{ cm}^3 \quad ,$$

$$\exp\left(-\alpha_{4P}\frac{x}{v}\right) = 8.87 \times 10^{-1} \quad ,$$

and

$$\sinh\frac{\alpha_{4P}\delta}{v} = 2.42 \times 10^{-2} \quad .$$

Putting all the above values together, one finds the power detected from Paschen α to be 3.58×10^{-17} watts, or 330 photons/sec.

REQUIRED BEAM CURRENT FOR λ 1.083 μ IN He I

For this calculation we assume the available detector has an NEP
of 10^{-14} watts. This corresponds to 2.18×10^5 photons/sec detected.
The intensity (photons/sec) at the detector a distance x cm from the
foil is given by

$$I(x) = k \, N_P \, A_{PS} \, \frac{2av}{\alpha} \exp\left(-\alpha_P \frac{x}{v}\right) \sinh \frac{\alpha_P \delta}{v} .$$

The factors k, x, a, and δ are the same as in Appendix E. We assume
$I(x) = 2.18 \times 10^5$ photons/sec, and use the equation to find N_p, the ini-
tial number of atoms/cm^3 in the 2 $^3P_1$ state of He I created at the foil
in one second. Using 300 keV for the particle energy, the velocity is
3.8×10^8 cm/sec. For the transition 2 $^3P_1 \rightarrow 1\ ^3S_1$, the transition
probability $A_{PS} = \alpha_P = 1.022 \times 10^7$/sec [Wiese, Smith, and Glennon 1966].
Using these values

$$N_P = \frac{I(0.5)}{k \, 2av \, \exp\left(-A_P \frac{x}{v}\right) \sinh \frac{A_P \delta}{v}} ,$$

$$N_P = 8.7 \times 10^2 \quad 2\ ^3P_1 \text{ atoms/cm}^3 .$$

The number of atoms in a μamp of He$^+$ beam per second is
6.25×10^{13} atoms/μamp sec. Dividing this value by the volume of the
beam per second (av), we find a one μamp beam of He$^+$ has

8.4×10^5 atoms/μamp cm^3.

The ratio of the number of 2 $^3P_1$ atoms/cm^3 to the number of atoms/cm^3 in a μamp of beam gives 1.04×10^{-3} μamp He$^+$ beam required to just detect λ 1.083 μ.

This calculation was made assuming all the beam was in the form of He I after the foil. From experiment [Martinson and Bickel 1970b, Table I], only 20% of the beam is He I and all of this is in the 2 $^3P_1$ state. If we now assume that the current from He$^+$ before the foil remains the same after the foil, then a 5.2×10^{-3} μamp beam of He$^+$ is needed to just detect λ 1.083 μ with the best detector.

SELECTED BIBLIOGRAPHY

Andrä, J., Physics Department, University of Arizona (private communication, January 1970).

Bashkin, S. (Ed.) Beam-Foil Spectroscopy, (Gordon and Breach, New York, 1968).

Berry, H.G., Bickel, W.S., Martinson, I., Weymann, R.J., and Williams, R.E., "Total Transition Probabilities for the Bowen Levels of O III" (to be published in the Astrophysical Journal, 1970).

Bethe, H. A. and Salpeter, E. E., Quantum Mechanics of One- and Two-Electron Atoms (Springer-Verlag, Berlin, 1957).

Bickel, W. S., Applied Optics 6, 1309 (1967).

Brancazia, P. J. and Cameron, A. G. W. (Eds.) Infrared Astronomy (Gordon and Breach, New York, 1968).

Conn, G. K. T. and Avery, D. G., Infrared Methods (Academic Press, New York, 1960).

Eastman Kodak Company: Kodak Wratten Filters (Publication No. B-3, Eastman Kodak Company, 1965).

Fink, U., Lunar and Planetary Laboratory, University of Arizona (private communication, January 1970).

Gray, D. E. (Ed.) American Institute of Physics Handbook, Second edition (McGraw-Hill Book Company, Inc., New York, 1963).

Hall, D., Kitt Peak National Observatory, Tucson, Arizona (private communication, January 1970).

Hudson, R.D., Jr., Infrared System Engineering (John Wiley and Sons, New York, 1969).

Longhurst, R.S., Geometrical and Physical Optics, Second edition (John Wiley and Sons, New York, 1968).

Low, F.J., Journal of the Optical Society of America 51, 1300 (1961).

Martin, Albert E., Infrared Instrumentation and Techniques (Elsevier Publishing Company, New York, 1966).

Martinson, I. and Bickel, W.S., "Beam-Foil Spectra of Boron in the Wavelength Region 450-2500Å" (to be published in Journal of the Optical Society of America, 1970a).

Martinson, I. and Bickel, W.S., "Mean Lives of the 2p ^{1}P, 3p ^{1}P, 4p ^{1}P, 5p ^{1}P Levels in He I", (to be published in Journal of the Optical Society of America, 1970b).

Moss, T.S. (Ed.), Infrared Physics $\underline{8}$, (1968).

Nicodemus, F.E., Journal of the Optical Society $\underline{59}$, 243 (1969).

Princeton Applied Research: Instruction Manual Precision Lock-in Amplifier Model HR-8 (Princeton Applied Research Corporation, Princeton, 1967).

Rao, N.K., Humphreys, C.J., and Rank, D.H., Wavelength Standards in the Infrared (Academic Press, New York, 1966).

Smith, R.A., Jones, F.E., and Chasmar, R.P., The Detection and Measurement of Infrared Radiation (Clarendon Press, Oxford, 1957).

Spex Industries: Spex Speaker, Vol. X, No. 3 (Spex Industries, New Jersey, 1965).

Weast, R.C. (Ed.), Handbook of Chemistry and Physics, 45th edition (Chemical Rubber Company, Cleveland, Ohio, 1964).

Weiss, A.W. (to be published in Physical Review 1970).

Wiese, W.L., Smith, M.W., and Glennon, B.M., Atomic Transition Probabilities, Vol. I (NSRDS-NBS4, U.S. Government Printing Office, Washington, D.C., 1966).

Wolfe, W.L., Handbook of Military Infrared Technology (Office of Naval Research, Washington, D.C., 1965).

Yager, R.E., "A Model for Beam-Foil Excitation of He$^+$" (Ph.D. Dissertation, Rice University, April 1969).