SPECTRAL ANALYSIS OF THE IMPACT OF ULTRA VELOCITY COPPER SPHERES INTO COPPER TARGETS

by

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ACKNOWLEDGMENT

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I wish to thank Bill Clark for his expert and selfless assistance in experiments and participation in stimulating discussions. I must also thank Dr. Paul Palmer for his contributions to such discussions.

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SUMMARY

Spectrographic observations were made for copper projectiles impacting into copper targets in various controlled atmospheres. Atomic copper lines are the predominant feature of the impact flash of copper-to-copper impacts in a medium of argon. Since a copper line with a 7.1 ev excitation energy is excited in an argon atmosphere, an energy of at least this magnitude is available for excitation of copper atoms. Results indicate that in argon, the flash is produced by micron-size copper particles ejected from the target, some with velocities no less than 6-7 km/sec and heated by the medium. A collision process between copper atoms evaporated from the heated spray particles and atoms of the argon atmosphere can account for the observed copper lines.

In a medium of hydrogen, the impact flash is dimmer by at least two orders of magnitude, giving a smooth spectral contour with no detectable line structure. However, no obvious black body temperature is obtainable from the contour of this light emission in hydrogen. The relative velocity between copper atoms and hydrogen molecules required to produce copper lines is greater than 20 km/sec in a collision process.

The reduced size of the flash in hydrogen indicates that the particles responsible for the flash are smaller than those producing the flash in argon. It appears that the size of the particles that produce the flash in each gas are of the order of magnitude of the mean free path of the molecules in that gas.

INTRODUCTION

Within the past few years, research in impact phenomena has received considerable interest. Of immediate importance has been the effect of impact of space satellites and rockets with high speed particles outside the earth's atmosphere. A bright flash is observed during hypervelocity impacts produced in the laboratory. An understanding of the nature of this light produced during collision may reveal some important features involved in the mechanism of cratering, which gives sufficient motivation for this research.

Earlier work[1] in this field has been done at the University by Thomas Lee. His investigation of the light produced by shooting copper spheres into copper targets in air revealed no spectral features on film placed at the focal plane of a spectrograph. He did, however, discover aluminum oxide bands and atomic lines of aluminum when shooting various materials into aluminum. In the present research, three photomultipliers mounted in the focal plane of a spectrograph monitored three separate wavelengths simultaneously and provided voltages proportional to the radiant flux per wavelength interval emitted from the impact area. These outputs were recorded on film by cameras mounted on three 535 Tektronix oscilloscopes. The sensitivity was sufficient to detect the spectral features of copper-to-copper impacts. In addition, a time axis was provided. Calibration techniques provided a quantitative measure of the power per wavelength interval radiated during the impact phenomena.

The experimental procedure was to place a copper target at one end of a vacuum chamber with a gun attached to the opposite end. The spectrograph

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[1] Unpublished research at the High Velocity Laboratory, University of Utah.

observed the flash through a window in the chamber. The use of a vacuum chamber allowed the type of gas and pressure of the gas surrounding the target to be varied.

Argon and hydrogen are convenient gases with differing physical and atomic properties. The spectral distribution of light in the range 460 to 630 mμ for copper-to-copper impacts in these two gases with a constant pellet velocity of 2.2 km/sec. is the topic of investigation of this report.

EXPERIMENTAL TECHNIQUE

The location and function of the experimental equipment are shown in Fig. 1. The photomultipliers were positioned along the focal plane of the spectrograph to monitor the desired wavelength intervals of the light produced by the copper-to-copper impact. The dynode voltages were set for high gain to adequately detect the relatively weak light of impacts in hydrogen. The gain was necessarily reduced to prevent saturation during the bright flashes in an argon atmosphere. The powder-loaded cartridge containing a 3/16" diameter copper sphere in a sabot (see Figs. 3 and 4) was used in the chamber of the special .22-caliber, smooth-bore gun. The function of the sabot was to eliminate interaction between the spherical pellet and gun barrel. When hydrogen was used, the vacuum range was evacuated using a Welch Duo Seal pump to an absolute air pressure of 1-2 mm of mercury. With the pump operating, hydrogen was introduced into the range and the rate of flow was adjusted to the pumping rate after atmospheric pressure was attained. This flushing process continued for 7 1/2 minutes, which is the time required to pump a volume of gas equal to five times the volume of the vacuum range. The exhaust hydrogen gas was safely piped out of the building. The hydrogen atmosphere within the range attained a purity essentially equal to the purity of the bottled gas, which is attested to be .9997 according to the supplier.

A pressure slightly greater than one atmosphere remained after the pump and entering hydrogen were shut off. After firing, the pump was turned on and the hydrogen was pumped out before air was allowed to fill the range. The plexiglass windows were washed with methyl alcohol after each shot to remove the explosion gas products.

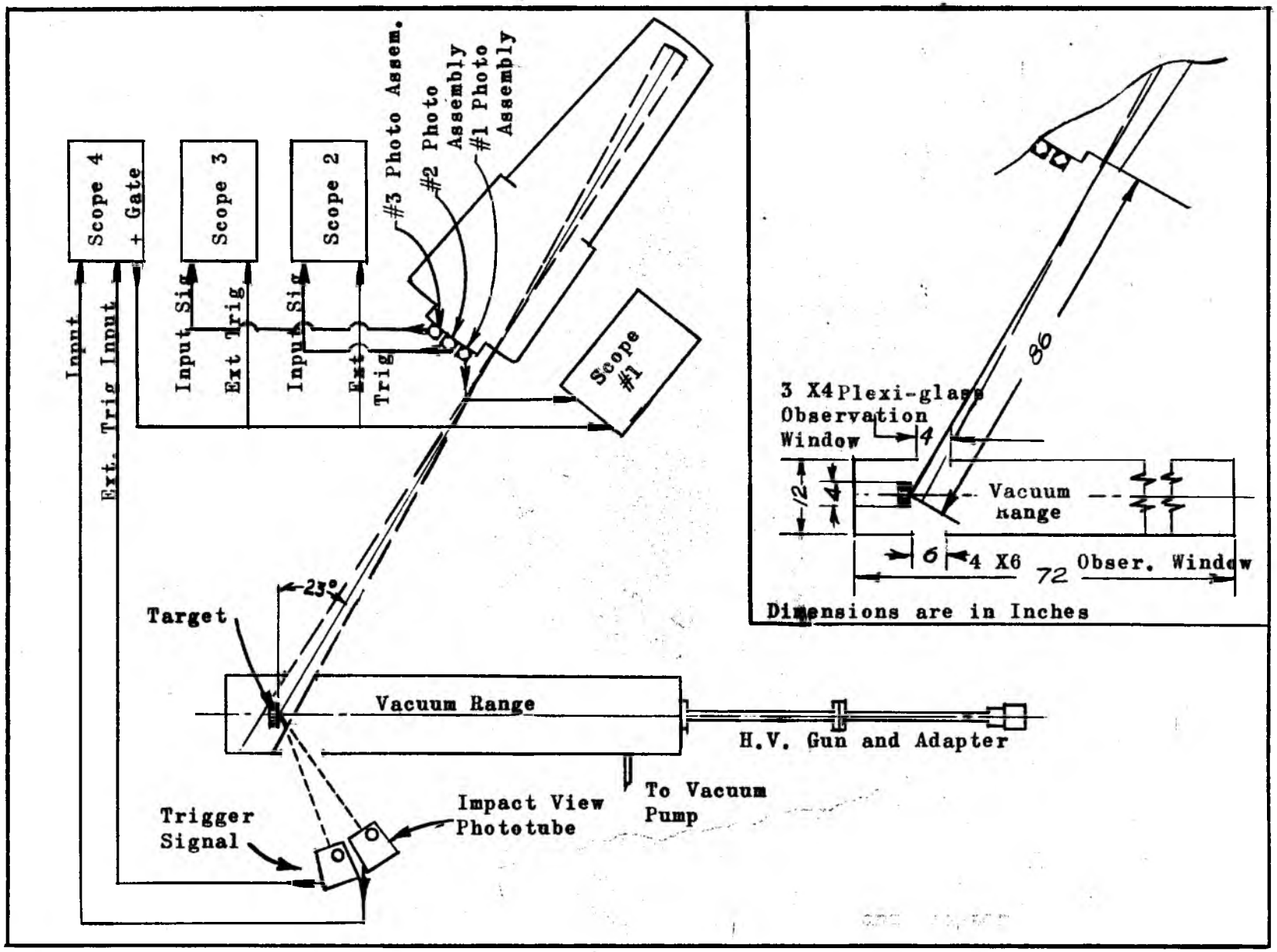

Fig. 1. Block Diagram of Experimental Apparatus

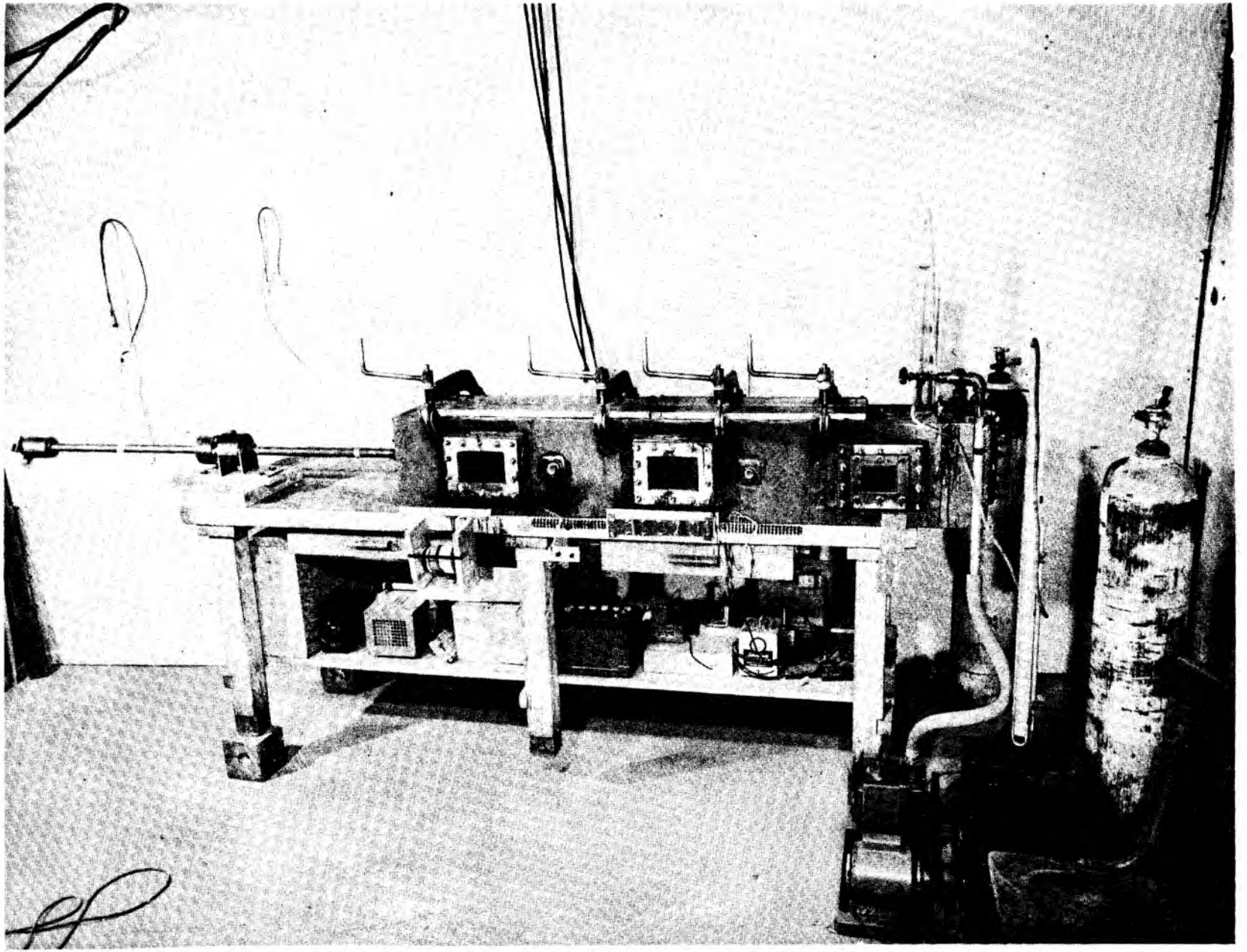

Fig. 2. Vacuum Range

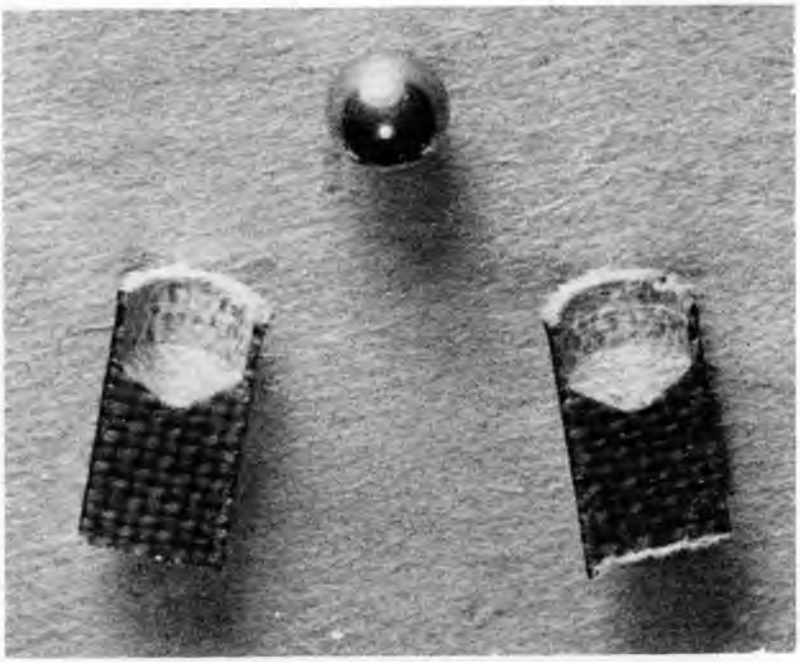

Fig. 3. Sabot and 3/16-in. copper sphere. The sabot, a phenolic cylinder (.22 in. dia.) with 3/16-in. hole at one end, is divided along the axis to aid in the sabot pellet separation.

Fig. 4. Swift cartridge with sabot and copper sphere. All cartridges used in this research were filled with 2 1/2 cc of 2400 Hercules Smokeless Powder and 1/2 cc of 4064 DuPont Rifle Powder in that order.

For copper-to-copper impacts in argon, the procedure was the same except that the flushing process was not used. The maximum impurity content of the argon gas surrounding the target during impact was one part in 30 as measured by partial pressures. This was determined from the leak rate of the vacuum range. Carbon dioxide was the only impurity that has a greater molecular weight than argon, 44 compared to 40 amu. The carbon dioxide impurity was about one tenth of a per cent.

The original plan was to collect data in gases of differing molecular weight but equal density. The density of hydrogen at atmospheric pressure was chosen as the density to be used since this was the greatest permissible density for hydrogen that could be used with safety. In argon, this corresponds to a pressure of 3 cm of mercury. However, it was found that separation of the copper sphere from the sabot was unreliable at this density. As a result it was found necessary to use an argon pressure of 6 cm of mercury. Sabot and pellet separation was necessary to time resolve the separate impacts of sabot and copper pellet.

The separation problem had to be endured when shooting in hydrogen. This problem was met by observing the entire visible spectrum with a phototube[2] as shown in Fig. 1. When an anomalous total light output or pulse shape was recorded, the data were rejected on the basis of insufficient sabot and pellet separation. In general, however, the data were considered to be equally valid.

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[2] See Fig. 23, p. 51, of the Appendix for a circuit diagram.

For pressure measurements, an absolute, oil manometer was used for low pressure readings. A mercury manometer, open to the atmosphere, was used at greater pressures.

Triggering of the oscilloscopes from the impact light was accomplished using another phototube[3]. The output voltage of this circuit rises from 0 to 50 volts within 0.02 μsec when pulsed with a light signal of very low intensity compared to the impact flash. The rise time was experimentally determined by using a low energy spark for an input signal. The oscilloscope used for viewing the output signal was triggered by antenna pickup of the spark radiation.

The spectrograph, a 1.5-m diffraction grating type made by Bausch and Lomb, was used without condensing optics. It was positioned so that the projection of the grating through the slit filled the window of the vacuum range (see Fig. 1). This condition gave the spectrograph the maximum view of the target area at the minimum distance from the target area. Alignment was accomplished by shining a bright lamp positioned at the focal plane and observing the light emerging from the entrance slit. The spectrograph was moved until this light just filled the plexiglass window.

Each photomultiplier was placed behind an exit slit at the spectrograph. These slits were 1.0 mm wide. The plate factor of the spectrograph is 1.05 mμ per mm. The entrance slit of the spectrograph had a width of 0.5 mm, giving the trapezoidal-shaped transmitted band a half-width of 1.05 mμ, corresponding to a distance of 1.0 mm along the focal plane. Positioning

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[3] See Fig. 24, p. 51, in the Appendix for a circuit diagram.

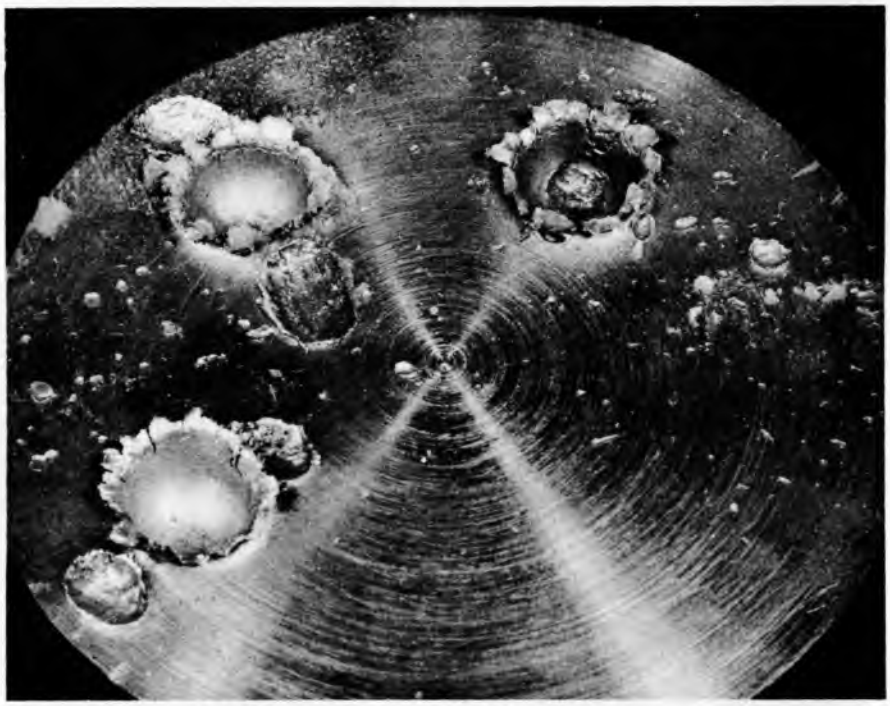


Fig. 5. Typical copper target after three impacts with 3/16-in. copper sphere shot at 2.2-2.4 km/sec. The impressions made by both halves of the sabot are clearly visible.

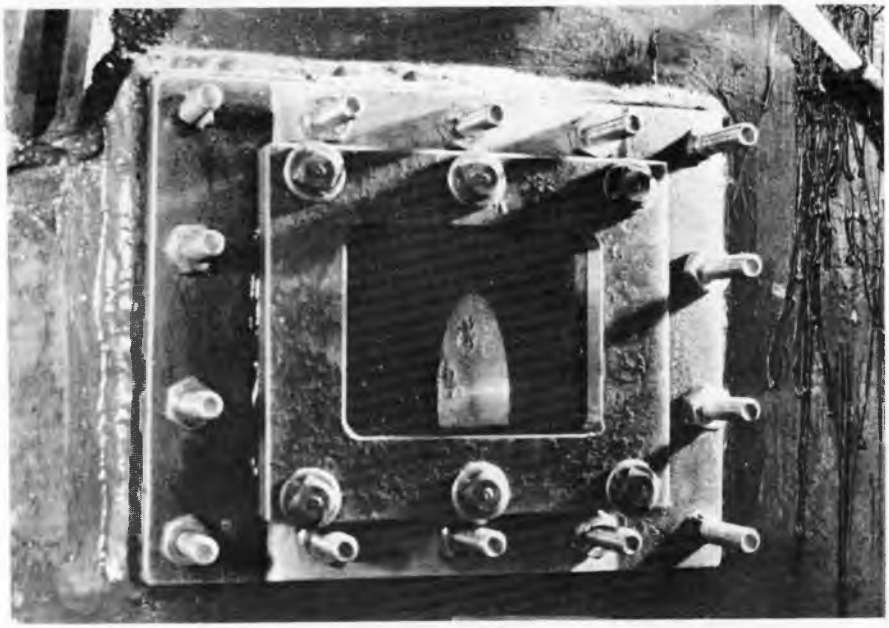


Fig. 6. View of the target from the entrance slit of the spectrograph.

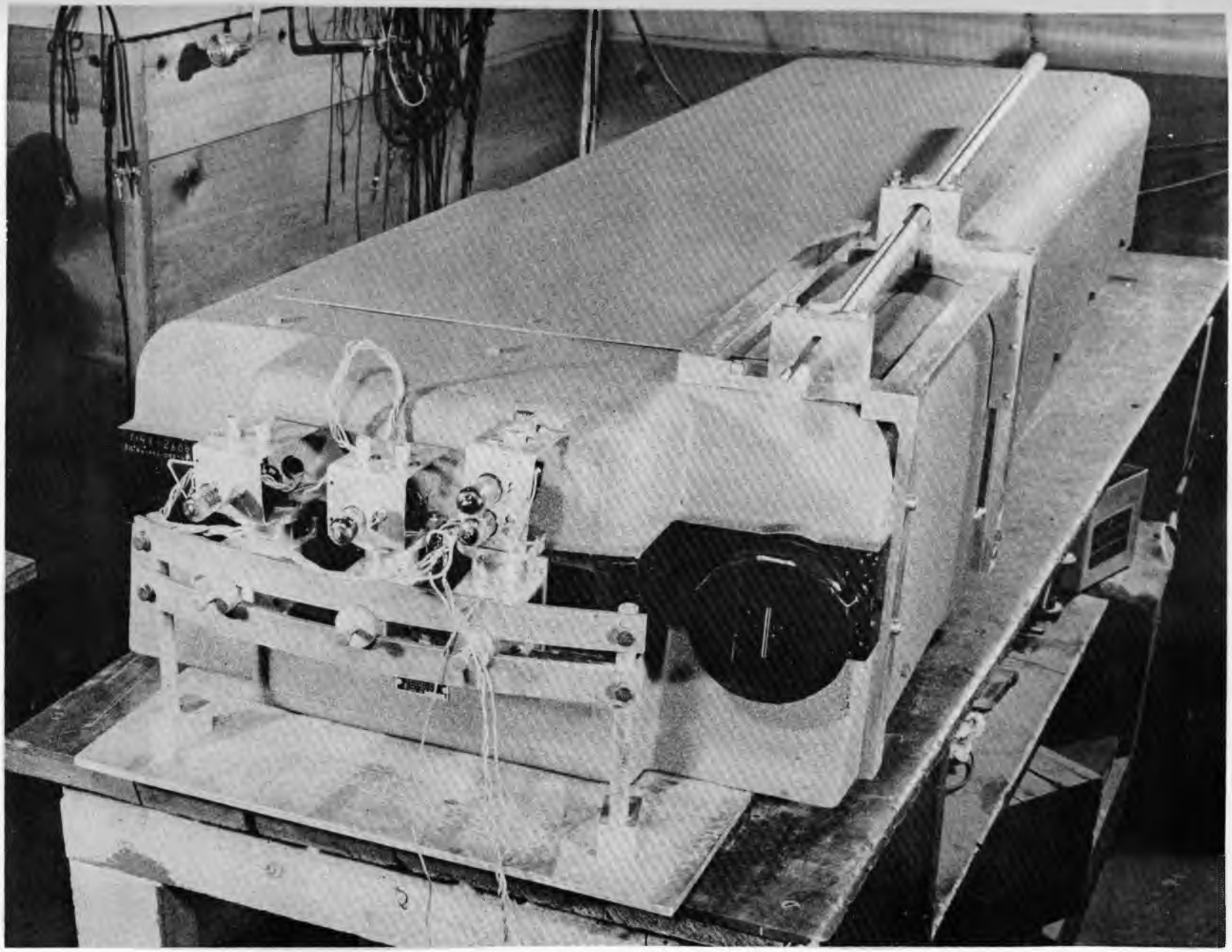
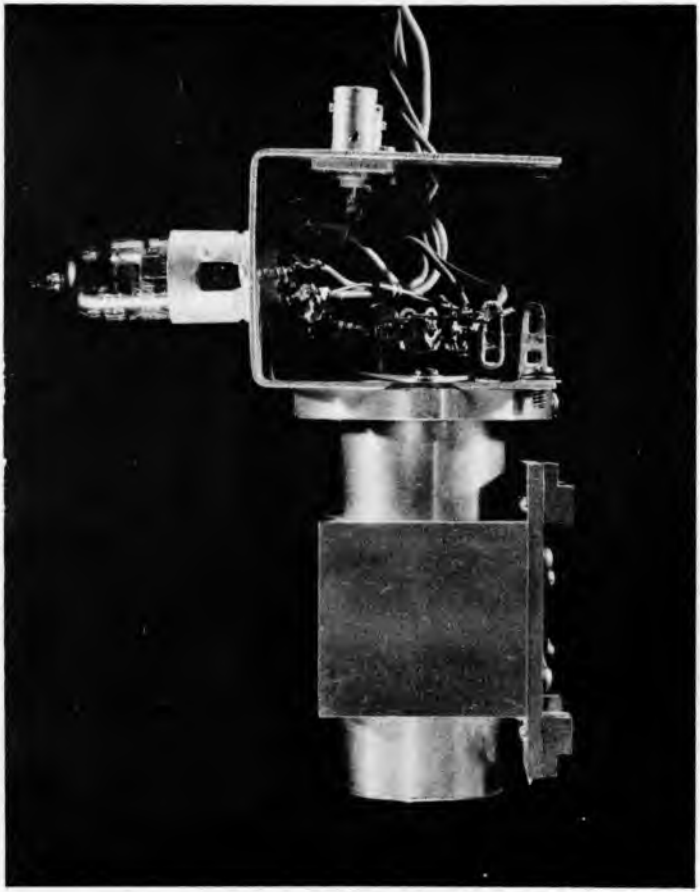
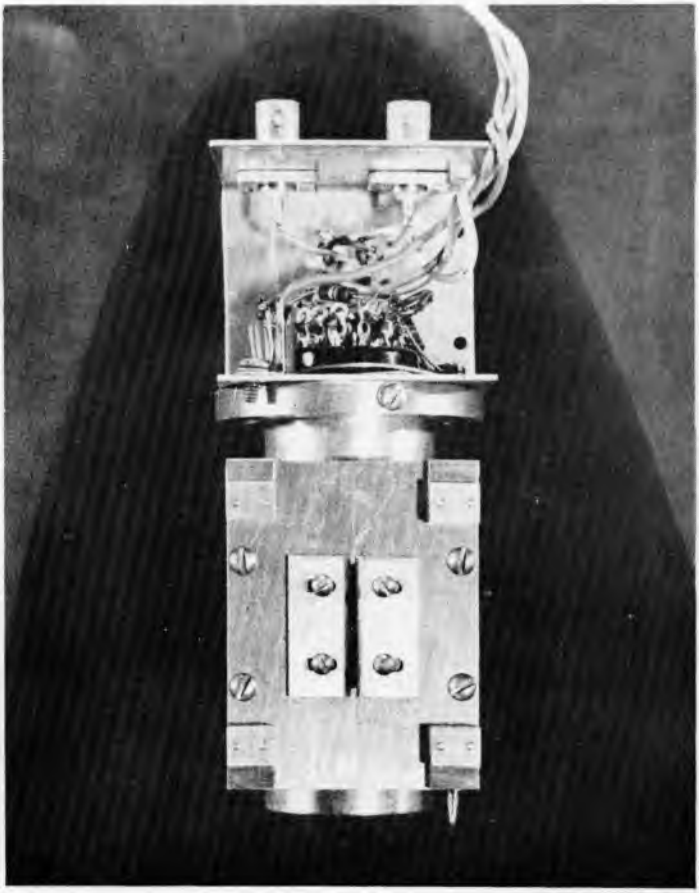


Fig. 7. Spectrograph (Bausch and Lomb), 1.5-meter, diffraction-grating type, is shown with three photomultiplier assemblies mounted at the focal plane.



Figs. 8a and b.



Photomultiplier Assembly

of the photomultipliers was reproducible to within 0.5 mm, making wavelength readings reliable to 0.5 mμ.

The wavelength settings for the photomultipliers were selected as follows. Strong atomic copper lines and one argon line were monitored. Wavelength positions adjacent to these lines but not coinciding with other known lines were monitored so that the existence or absence of the strong lines could be definitely established. These latter settings and others as free as possible from line contamination established the background readings.

The plate current of the photomultipliers was found experimentally to be nearly proportional to the total power of the radiation received by the cathode for a given dynode voltage and spectral region.[4] There was no non-linearity detectable in the plate current up to 0.1 ma and only a few per cent up to 0.3 ma. Using a plate resistance of 10 K, output voltages up to 3 volts were accepted as correct representation of the input light signal.

The measured rise time[5] of the photomultiplier circuits was about 0.2 μsec. The fastest rising impact flashes rise with uniformity to a peak in about 1.5 μsec (see Fig. 13). There is little doubt that the photomultipliers followed the light intensity of the impact flash with very little error.

Calibration[6] of the entire optical system with each photomultiplier was necessary before the output voltages of the photomultiplier circuits could be

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[4] See linearity determination in the Appendix, p. 38.

[5] See rise time determination in the Appendix, p. 42.

[6] See Appendix for absolute illumination calibration procedure, p. 42.

converted to a measure of absolute power of radiated light per unit wavelength. This calibration was accomplished and a graph[7] was drawn for the output voltage of each photomultiplier circuit for a hypothetical 1 $\mu watt/cm^2/m\mu$ of illumination at the entrance slit of the spectrograph as a function of wavelength for a dynode voltage of 61 volts. The output voltage versus dynode voltage graphs[8] were used to adjust the peak photomultiplier voltage, as measured with the polaroid camera pictures, to correspond to the standard dynode voltage of 61 volts. The illumination per millimicron on the entrance slit due to the impact was then determined by taking the ratio of the adjusted output voltage to the voltage that would have been obtained from a source supplying 1 $\mu watt/cm^2/m\mu$ illumination.

The conversion to total watts per millimicron of power radiated by the impact flash was made by multiplying the impact flash illumination at the slit of the spectrograph by $4\pi r^2$ where r, equal to 218 cm, is the distance from the center of the impact area to the entrance slit. This point source approximation appears quite reasonable since the dimensions of the flash are small compared to r. The entire flash is in view of the spectrograph and only a small part of the light reflected by the copper target is reflected into the spectrograph's entrance slit.

A few open-shutter pictures were taken of impacts in the hydrogen and argon atmospheres. A sample of each is presented in Fig. 14 and Fig. 15, respectively.

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[7] See Fig. 21 in the Appendix, p. 45.

[8] See Figs. 17, 18, and 19 in the Appendix, pp. 39-41.

RESULTS

The observed spectral distribution[9] for copper-to-copper impacts in argon at 6 cm of mercury (Fig. 9) and in hydrogen at 63.5 cm of mercury, or atmospheric pressure (Fig. 10), constitutes the primary results of this research. Included in this section are typical data pictures of the output of the photomultipliers for each gas, shown in Figs. 12 and 13, and an open-shutter picture of the impact flash in each gas, shown in Figs. 14 and 15. These photographs present the time scale and geometrical size of the flash.

The predominant features of the spectral distribution curve in argon are the copper lines at 465.1 mμ, 510.6 mμ, 570.0 mμ, and 578.2 mμ. The transition and excitation energies corresponding to these lines are indicated on the energy level diagram of copper shown in Fig. 11. The excitation energy required to produce the copper lines at 510.6 mμ, 570.0 mμ, and 578.2 mμ is 3.5 ev. The excitation energy required to produce the 465.1 mμ copper line is 7.1 ev, which provides a very important result: 7.1 ev represents a lower bound to the excitation energy available to the copper atom during copper-to-copper impacts in argon.

Failure to detect the strong argon line at 565.1 mμ is indication that argon lines are either absent or undetectable above the background.

The energy level diagram of argon[10] shows that a minimum excitation energy of 14.8 ev is necessary to produce the line at 565.1 mμ. The minimum

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[9] See the Appendix, pp. 52 and 53, for tabulated data.

[10] American Institute of Physics Handbook, sec. 7, pp. 33 and 60.

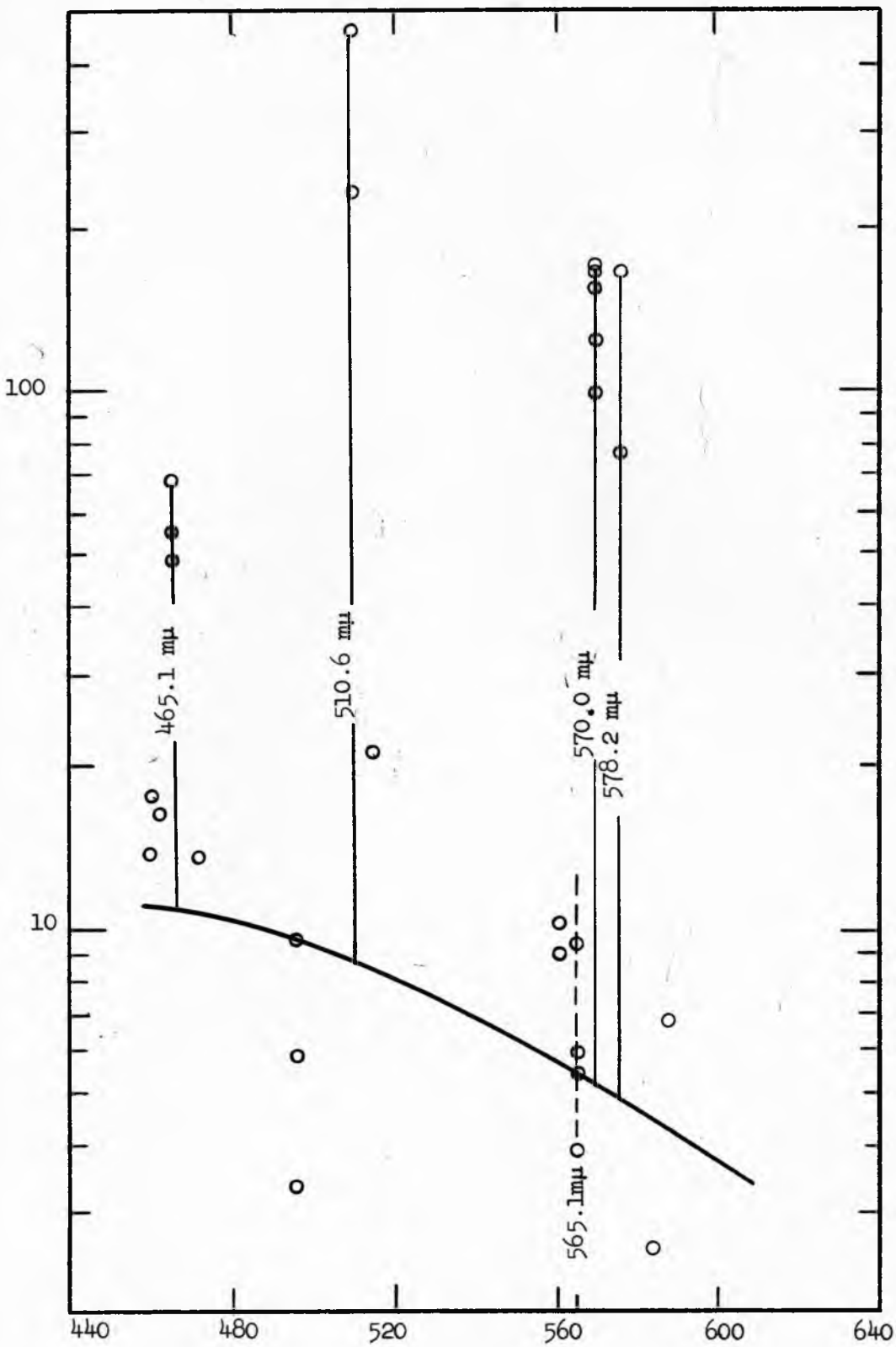

Fig. 9. Total watts/mμ radiated by the impact flash in argon at 6 cm of mercury versus wavelength in mμ. All data points are indicated. The observed copper lines are indicated. The argon line at 565.1 mμ shown by the vertical dash line was not observed.

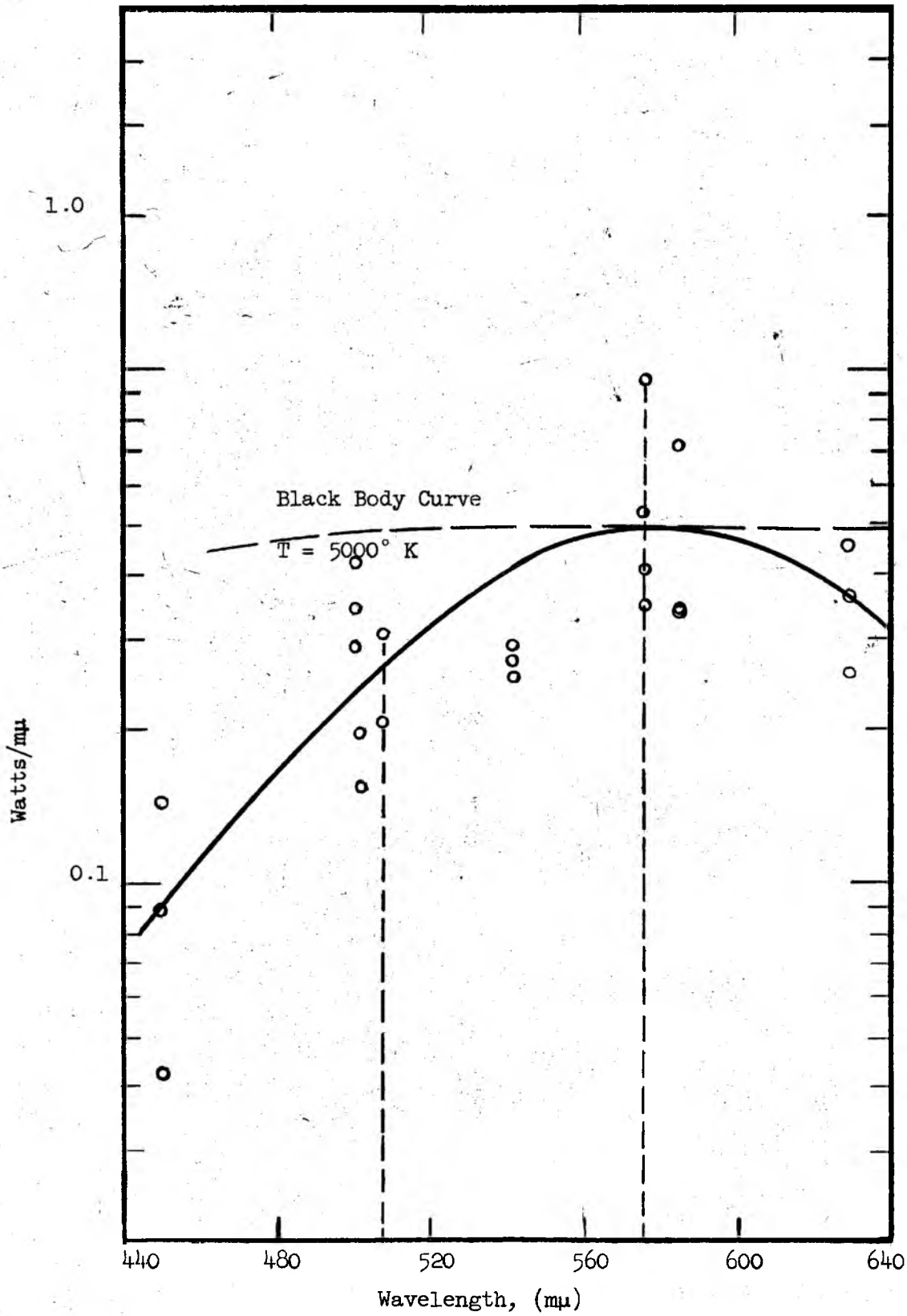

Fig. 10. Total watts/mμ radiated by the impact flash in hydrogen one atmosphere of pressure versus the wavelength in mμ. All data points are indicated. The positions of the two monitored copper lines are indicated by the vertical dashed lines.

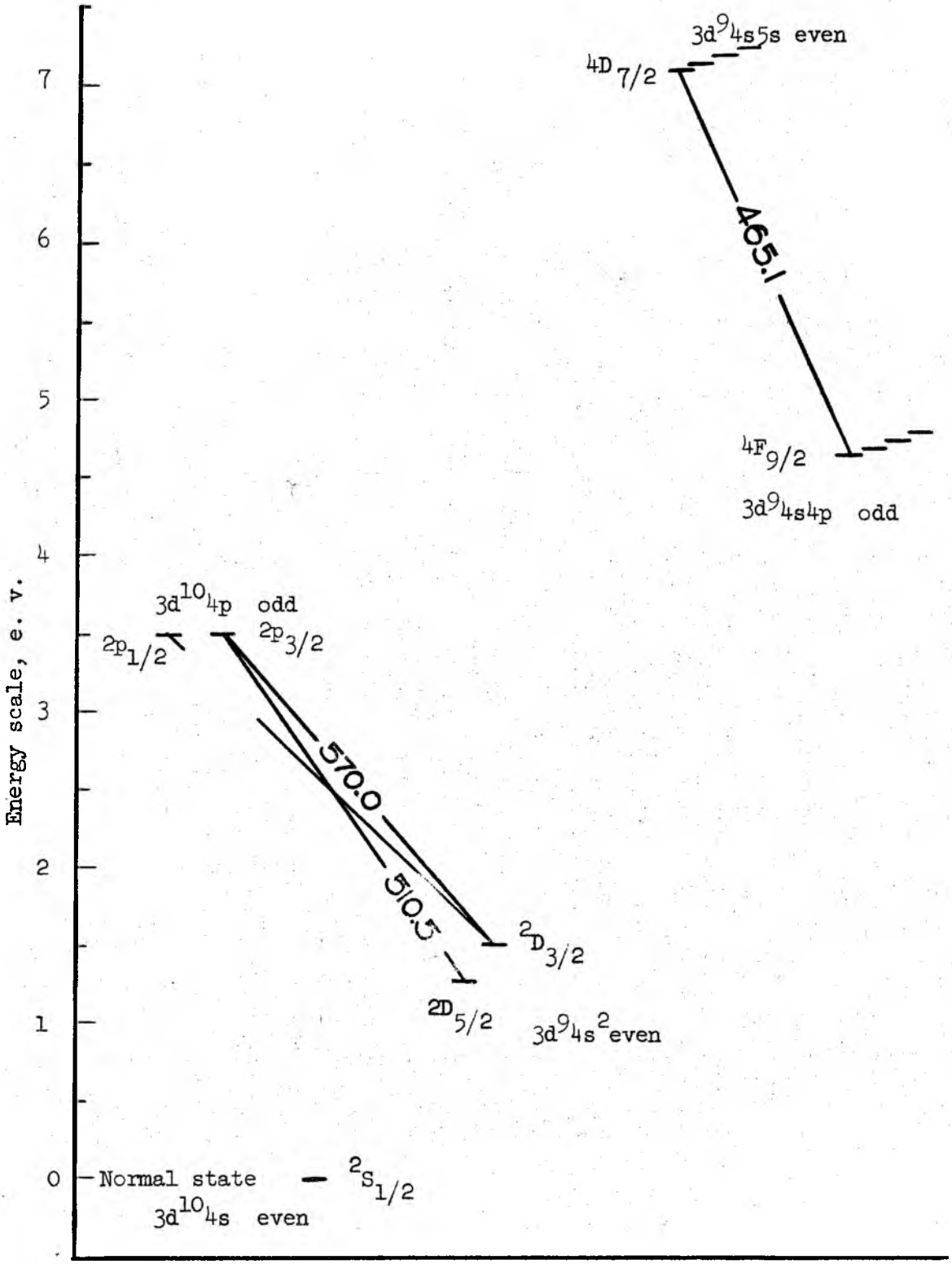

Fig. 11. Energy level diagram of copper. After H. E. White, Introduction to Atomic Spectra, p. 395. Identification of the transitions corresponding to the indicated lines and energies of the transition levels are from A. S. Shenstone, Phil. Trans. Roy. Soc.1949, Vol. 241, p. 297.

excitation potential of argon is 11.4 volts, but the minimum excitation energy necessary to produce any persistent lines of argon between 460 and 630 mμ is 14.4 ev.

The differences between the spectral curves of the copper-to-copper impacts in argon and hydrogen are striking. The impact flash in hydrogen is much dimmer and contains no detectable copper lines. The curve in Fig. 9 represents a visual fit to the argon data between the strong copper lines. Because of the possible presence of unresolved line structure for impacts in argon, the background curve undoubtedly represents both discrete and continuous light emission. No attempt was made either to measure or to represent the widths of the observed copper lines. The curve in Fig. 10 represents a visual fit to the hydrogen data and is compared to a black body radiation curve for a temperature of 5000° K.

There is no quantitative way of estimating the accuracy of the total watts per millimicron radiated by the impacts. The absolute calibration of the equipment could introduce errors as large as a factor of 2, while the relative calibration is probably good to within 10%.

The total light of the flash in argon, as measured by the impact-viewing phototube, was found to reproduce to within 10%. The greater scatter in the photomultiplier data appears to represent variations in the spectral distribution of the impact flash from one shot to another.

It is difficult to estimate how much of the data scatter in hydrogen is caused by insufficient sabot separation. The total light as measured by the impact-viewing phototube varied by as much as a factor of 3.

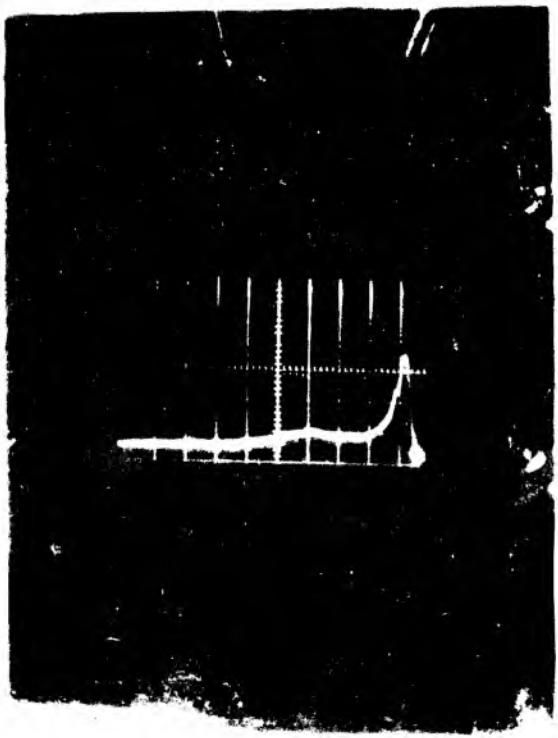

Fig. 12. Typical output from a photomultiplier when viewing copper-to-copper impacts in argon at 6 cm of mercury. The time base is 5 μsec per major horizontal division and increases from right to left.

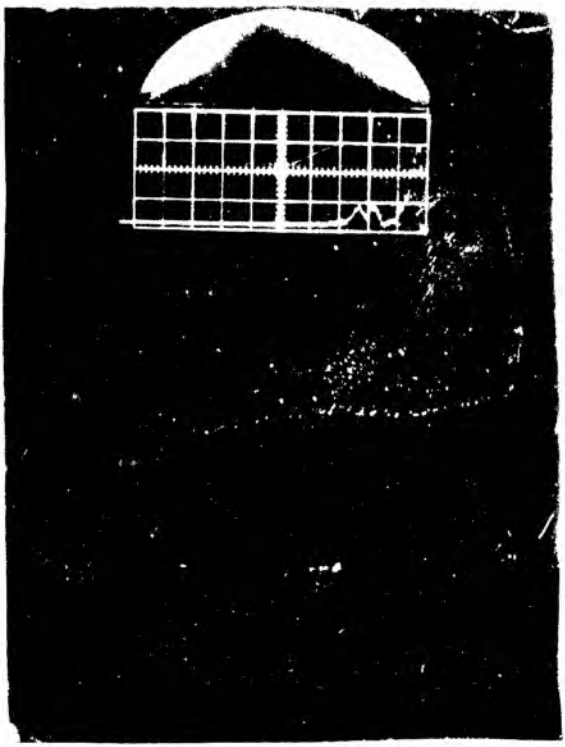

Fig. 13. Typical output from a photomultiplier when viewing copper-to-copper impacts in hydrogen at atmospheric pressure. The time base is 5 μsec/cm and increases from right to left.

Fig. 14. Copper-to-copper impact in argon at 6 cm of mercury.

This photograph was taken with an open-shutter camera. Vacuum range window dimensions: 6 in. x 4 in.

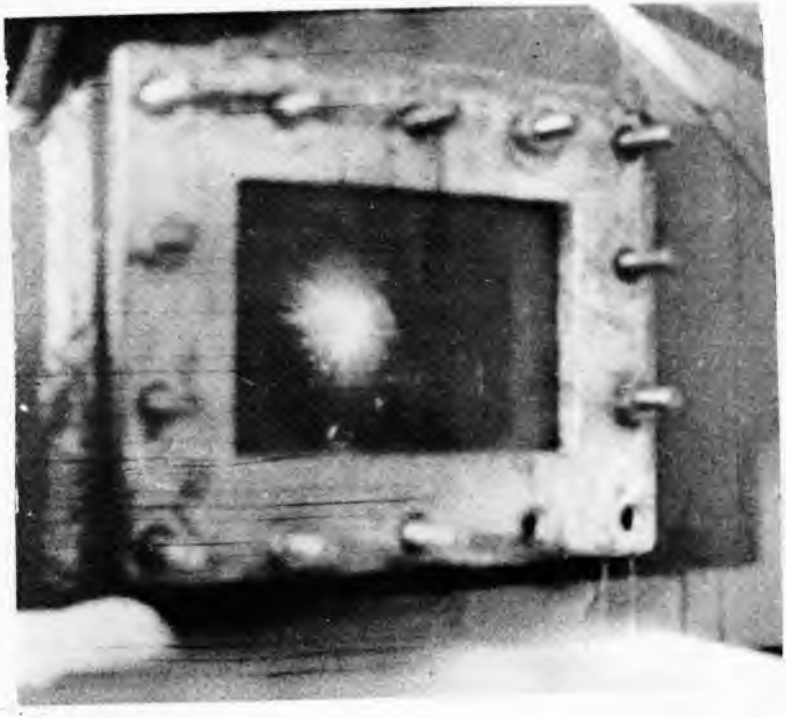

Fig. 15. Copper-to-copper impact in hydrogen at a pressure of one atmosphere.

This photograph was taken with an open-shutter camera. Vacuum range window dimensions are 6 in. x 4 in.

There was no apparent correspondence between this variation of total light and the light measured by the photomultipliers. This is quite possibly a geometrical effect since the phototube views the impact through a different window in the vacuum chamber. A normalization procedure was tried in an attempt to smooth the data obtained in separate shots. This scheme failed to improve the spectral curves.

The radiation in the hydrogen medium comes to a peak in about 1.5 μsec after the start of radiation, compared to about 3.5 μsec for argon. The radius of the luminous flash region in hydrogen is about 2 cm. It is about 4 cm in argon.

While investigating the effect of impurities on the spectrum produced in hydrogen, no detectable difference was observed when up to 10 cm of mercury pressure of nitrogen was added to the hydrogen. Bright flashes are known to occur in nitrogen at this partial pressure during copper-to-copper impacts, so the hydrogen appears to quench the normally bright nitrogen flash. Further investigation of this effect is recommended.

ANALYSIS OF DATA AND THEORETICAL CONSIDERATIONS

THEORY OF LIGHT-PRODUCING MECHANISM

The large difference in light produced for copper-to-copper impacts in an argon atmosphere as compared to that in a hydrogen atmosphere shows that the major light-producing mechanism involves an interaction with the gas surrounding the cratering area. The strong copper line features of the impact spectrum in argon provide good evidence that collisions are involved between copper and argon atoms with energies sufficient to excite copper sufficiently to radiate the observed lines.

Another clue to the light-producing mechanism is the time interval between initial impact and the maximum power output of the light produced during the flash. The doubly fast build-up to peak power output in hydrogen as compared to argon provides further evidence that the gas medium is significant and that the light output is not completely determined by the time scale of the cratering process. The size of the flash area is also a clue to the size of particles that are responsible for the flash.

In view of the above observations, the following light-producing mechanism for hypervelocity impacts is suggested:

Upon impact, small particles in the 1 μ range are ejected from the target, some being ejected at velocities greater than that of the impacting pellet. These copper particles shall be referred to as "spray particles". The spray particles that contribute to the observed light are then heated by their travel through the gas medium, and copper atoms are evaporated from the surface of these particles. The evaporated copper atoms collide

with molecules of the surrounding gas. Spectral lines of atomic copper are emitted when the energy transfer from the collisions is sufficient for excitation of the copper atoms. Continuous radiation is provided by the hot spray particles, each radiating a solid body spectrum according to its temperature.

VELOCITY OF LUMINOUS SPRAY PARTICLES

Since the energy transfer to copper atoms is much greater during collisions with argon atoms than with hydrogen molecules for the same relative velocities, the preceding theory can account for the copper line structure observed for impacts in argon as well as the absence of detectable copper lines in hydrogen. Assume that some spray particles travel fast enough to provide their evaporated copper atoms with sufficient kinetic energy to be excited by collisions with argon atoms, but insufficient kinetic energy to be excited by collisions with the hydrogen molecules. From this assumption, upper and lower bounds can be placed on the maximum velocity of the copper spray particles. Most of the energy received by a copper atom prior to vaporization is used to free itself from the surface. The energy of vaporization of copper is 3.12 ev/atom.[11] Only a small fraction of this energy is available as kinetic energy of the evaporated atom. This kinetic energy will be small compared to the 7.1 ev. necessary to obtain the observed copper line at 465.1 mμ. In the following calculations, the velocities of the evaporated copper atoms relative to their emitting surfaces are assumed to be negligible.

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[11] American Institute of Physics Handbook, sec. 4, p. 139.

Let V be the spray particle velocity, M the mass of the copper atom, and let m be the mass of the argon atom. If it is assumed that collision with argon atoms is responsible for the 7.1 ev excitation of copper atoms, a minimum value of V can be calculated for the spray particles, giving rise to the observed atomic lines of copper. Assume that the initial velocity of the argon atoms is zero since their kinetic energy is of the order of 3/2 kT where kT is about 1/40 ev at room temperature. Maximum excitation energy occurs during perfectly inelastic collisions. Conservation of momentum in the lab system requires,

$$MV = MV_1 + mV_1$$

$$\text{or} \quad V_1 = \frac{M}{m+M} V \tag{1}$$

where V_1 is the velocity of both the copper atom and the argon atom after collision.

Applying the conservation of energy requirement,

$$\frac{1}{2} MV^2 = \frac{1}{2} (M+m) V_1^2 + E$$

where E is energy available for excitation of copper.

$$E = \frac{1}{2} MV^2 - \frac{1}{2} \frac{M^2}{M+m} V^2 = \frac{1}{2} MV^2 \frac{m}{M+m}$$

$$V = \sqrt{2E \frac{(M+m)}{Mm}} \tag{2}$$

For an observed excitation energy of

$$E = 7.1 \text{ ev} = 1.14 \cdot 10^{-18} \text{ joules}$$

$$\text{and } M = 64 \text{ amu} = 1.06 \cdot 10^{-25} \text{ kg}$$

$$m = 40 \text{ amu} = 6.64 \cdot 10^{-26} \text{ kg}$$

$$\text{we find } V = 7.46 \text{ km/sec}$$

V is a "threshold velocity" which refers to the velocity of the slowest spray particles that could theoretically be capable of producing 7.1 ev copper excitation.

The threshold velocity of spray particles is 7.46 km/sec if the observed 7.1 ev copper excitation is accomplished by a single collision with argon. The average time, $\bar{t}$, for a collision of a copper atom is

$$\bar{t} = \frac{D}{V}$$

where V is the velocity of the evaporated copper atom and D is the mean average distance between collisions. D is approximately the same as the mean free path S of the medium, given by the expression,[12]

$$S = \frac{.225}{Nd^2} \qquad (3)$$

where N is the molecular density and d is the molecular diameter.

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[12] Karl R. Spangenburg, Vacuum Tubes, 1948, p. 753.

For argon, using the values

$$N = 2.1 \cdot 10^{18}$$

and $$d = 2.9 \cdot 10^{-8} \text{ cm}$$

gives $$S_A = 1.27 \cdot 10^{-4} \text{ cm}$$

and $$\bar{t} = 1.7 \cdot 10^{-10} \text{ sec}$$

The time required to emit a photon is of the order of 10^{-8} sec. Between 10 and 100 collisions with argon are possible during this time interval. If multiple collisions are assumed to be significant, the threshold velocity determination is modified by a collision factor,[13] J_n, such that

$$V = J_n V_n$$

where V_n is the threshold velocity for n inelastic collisions and

$$J_n = \sqrt{1 + \frac{a(1-a^{n-1})}{1-a}}$$

where $$a = \frac{M^2}{(M+m)^2}$$

For copper atoms in argon, a = .378. Therefore,

$$J_1 = 1 \text{ (corresponding to a single collision)}$$

$$J_2 = 1.174$$

$$J_3 = 1.24$$

$$J_\infty = 1.27$$

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[13] See Appendix, p. 47, for derivation.

The threshold spray particle velocity, assuming an infinite number of inelastic collisions of the evaporated copper atom with argon atoms would be 5.87 km/sec.

If enough copper vapor is produced by spray particles, it becomes important to consider high energy collisions between evaporated copper atoms and copper atoms left behind from preceding spray particles. It is interesting to observe that insufficient vapor is produced to observe copper lines during impacts in the hydrogen atmosphere. But this question is unsettled for argon, so a threshold velocity of spray particles should also be calculated for single and multiple collisions of copper atoms with copper atoms. The preceding equations are still applicable when m is replaced by M. So, from Eq. (2),

$$V = \sqrt{\frac{4E}{M}} = 6.56 \text{ km/sec}$$

for one inelastic collision,

and $a = 1/4$

$J_1 = 1$

$J_2 = 1.12$

$J_3 = 1.14$

$J_\infty = 1.15$

For an infinite number of inelastic collisions, the threshold velocity would be $\frac{6.56}{1.15} = 5.70$ km/sec.

Research in the direct measurements of spray particle velocities has recently been in progress at this laboratory. Tentative findings corroborate the existence of spray particles which travel in the velocity range as calculated in this section.

SIZE OF LUMINOUS SPRAY PARTICLES

The impact flash builds up to maximum radiated power twice as fast in hydrogen as in argon. By the proposed theory, it appears that smaller, and possibly faster, spray particles produce the light observed in hydrogen. This does not mean that the size distribution of particles is necessarily different in the two gases, but only that the smaller particles are responsible for the observed light in hydrogen. This hypothesis is confirmed by the open-shutter pictures of the impacts. These pictures show that the radius of the luminous spray is smaller in hydrogen than in argon. This is true in spite of the fact that the drag forces on the spray particles in hydrogen are less because the density of the hydrogen at atmospheric pressure is half that of the argon at 6 cm of mercury pressure. A smaller spray radius leads immediately to the conclusion that smaller spray particles are responsible for the observed impact light in hydrogen.

The size of spray particles can be approximately determined by using the size of the impact flash as observed by the open-shutter pictures.

Opik gives the following equation[14] pertaining to the deceleration of small particles in a gaseous medium:

$$\frac{dV}{dt} = - \frac{kB\rho V^2}{4r\rho_c}$$

where k = deceleration factor

B = shape factor

V = velocity of particle

r = radius of particle

ρ = density of medium

ρ_c = density of particles

For velocities under 12 km/sec, k varies from 1 to 0.52, depending on the thickness of gas cap on the particles. Unity corresponds to no gas cap, while 0.52 corresponds to an infinitely thick cap.

The shape factor B for a sphere is 3 and represents the minimum value.

Let K be defined by the equation

$$\frac{dV}{dt} = -K \frac{V^2}{r}$$

also $ds = V\, dt$

substituting

$$V \frac{dV}{dS} = - K \frac{V^2}{r}$$

$$\int_{V_o}^{V_1} \frac{dV}{V} = \int_{0}^{S_1} - \frac{K}{r}\, dS$$

[14] E. J. Opik, Physics of Meteor Flight in the Atmosphere, p. 57.

where S_1 is the radius of the impact flash, V_1 is the spray particle velocity at S_1, and V_o is the initial spray velocity.

Integrating,

$$\ln\left(\frac{V_o}{V_1}\right) = \frac{K}{r} S_1$$

$$r = \frac{KS_1}{\ln\left(\frac{V_o}{V_1}\right)} .$$

Assuming spheres, for which

$$B = 3$$

and $$k = 1$$

which will set an upper limit to the spray particle radius, and using, for copper spray in 1 atmosphere of hydrogen,

$$\rho = 6.7 \cdot 10^{-5} \text{ g/cm}^3$$

$$\rho_c = 8.3 \text{ g/cm}^3$$

gives

$$K_H = \frac{kB\,\rho}{4\rho_c} = 6 \cdot 10^{-6}$$

The distance S_1 traveled by the luminous particles in hydrogen is about 2 cm according to the open-shutter pictures. The greatest uncertainty in the calculation of r is the ratio of the initial velocity to the velocity for which radiation essentially ceases. If the ratio of the initial velocity

to the terminal velocity for luminosity of the spray particles is assumed to be 2, i.e., $\frac{V_o}{V_l} = 2$, the radius of the luminous spray particles in hydrogen becomes $r_H = 1.7 \cdot 10^{-5}$ cm. Using the values of $d = 2.4 \cdot 10^{-8}$ cm and $N = 2.23 \cdot 10^{19}$ in Eq. (3), the mean free path for hydrogen becomes $1.75 \cdot 10^{-5}$ cm.

K_A for argon equals $12 \cdot 10^{-6}$ since the argon density was twice that of the hydrogen. The distance traveled by the particles in argon is about 4 cm. Assuming the same value for the ratio $\frac{V_o}{V_l}$, the radius of the spray particles in argon becomes $r_A = 0.68 \cdot 10^{-4}$ cm. The mean free path for argon at this density, as previously calculated, is $1.27 \cdot 10^{-4}$ cm.

According to Opik[15], the thickness of the gas cap is .75 times the radius of the particle. Therefore, it appears that the luminous spray particles are those with gas caps whose thicknesses are roughly the same as the mean free path of the medium. The heating of such particles is much more efficient than it is for larger particles because the gas cap fails to protect the particle from direct collisions.

BLACK BODY CHARACTER AND TEMPERATURE CONSIDERATIONS OF IMPACT FLASH IN A HYDROGEN ATMOSPHERE

Because no line structure is detectable in the hydrogen data, it is assumed that the observed light is the result of a black body type of radiation from the spray particles. No obvious black body temperature is obtainable from the contour of light emission in hydrogen. Copper boils

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[15] Ibid. p. 81.

at 2855° K. If this represents the maximum temperature of spray particles, the maximum total radiated power per unit area, L, is given by the equation

$$L = \beta T^4 = 5.67 \cdot 10^{-12} (2855)^4 = 374 \text{ watts/cm}^2$$

The area of the luminous spray region is about 10 cm^2. The total surface area of the individual spray particles is certainly much less than this. Assume the total emitting area to be 0.1 cm^2. Then, the total power radiated would be 37.4 watts. At the boiling temperature the black body radiation curve peaks at 1,260 mμ. The radiant power emitted between 500 to 600 mμ from a black body is clearly less than 1% of the total. Therefore, the maximum radiated black body power from 0.1 cm^2 at the boiling temperature of copper between these wavelengths is 0.374 watts. Integrating under the spectral curve obtained in hydrogen between these same wavelength limits gives a value close to 35 watts.

Since there is insufficient radiation from a black body at 2855°K to account for the data, the luminous spray particles must be hotter than 2855° K if the black body mechanism is correct. It is possible that metastable states for liquid copper are available at temperatures above boiling.

Assuming, then, that the observed light from impacts in hydrogen is a true continuum, consider a black body curve that peaks at 580 mμ, as the background in hydrogen does. This peak corresponds to a temperature of 5000° K giving L = 3550 watts/cm^2. The area under this black body curve between 500 to 600 mμ is about 10% of the total area, providing 35.5 watts for a 0.1 cm^2 spray particle area. The assumed 0.1 cm^2 radiating area at

this temperature thus accounts for the total observed power, although the observed spectral distribution does not conform to black body radiation.

The reduced radiation in the blue region of the spectrum for impacts in hydrogen might be explained if there were superheated spray particles for which the emissivity is a strong function of wavelength.

Before it can be reasonably assumed that the background radiation in hydrogen is a true continuum, other possibilities must be considered. If this light were unresolved atomic lines, the lines could conceivably be due to atoms of sufficiently low excitation impurities contained in the hydrogen or the copper. Such lines cannot possibly be unresolved copper lines since the strong copper lines found in an argon atmosphere do not show up in a hydrogen atmosphere. To produce copper lines in hydrogen requires a relative velocity greater than 20 km/sec between the copper atoms and hydrogen molecules in a collision process. Investigating the effects of an impurity in hydrogen, it was discovered that when 10 cm of mercury pressure of nitrogen was added to the essentially full atmosphere of hydrogen, no difference in the light output of the flash was observed. Pure nitrogen is known to produce a bright flash for copper-to-copper impacts. In addition, electrolytic copper is known to be of very high purity. For these reasons, impurities are thought not to contribute to the observed light output in hydrogen.

APPENDIX

MEASUREMENT OF PHOTOMULTIPLIER OUTPUT VOLTAGE

Because of the dc voltage present on the output of the cathode follower used in each photomultiplier circuit, a variable power supply was placed in series with the cathode follower and adjusted to balance the constant voltage of the cathode follower. With this procedure, it was possible to use a sensitive voltmeter, a 535 Tektronix oscilloscope, to directly measure output voltages of the photomultipliers and enable the following calibrations to be made.

WAVELENGTH CALIBRATION

To enable a wavelength calibration of the position of the exit slits in front of each photomultiplier to be made, a millimeter scale was placed along the focal plane of the spectrograph and a pointer was mounted on each photomultiplier holder. Using a mercury vapor source to illuminate the grating, the position of each photomultiplier pointer was observed for maximum output voltage on the green line at 546.1 mμ. Relative wavelength positions in the focal plane of the spectrograph were obtained using photographic techniques. The plate factor of the spectrograph proved to be a constant, 1.05 mμ per millimeter. A straight line giving wavelength vs. photomultiplier position was plotted. These curves appear in Fig. 16.

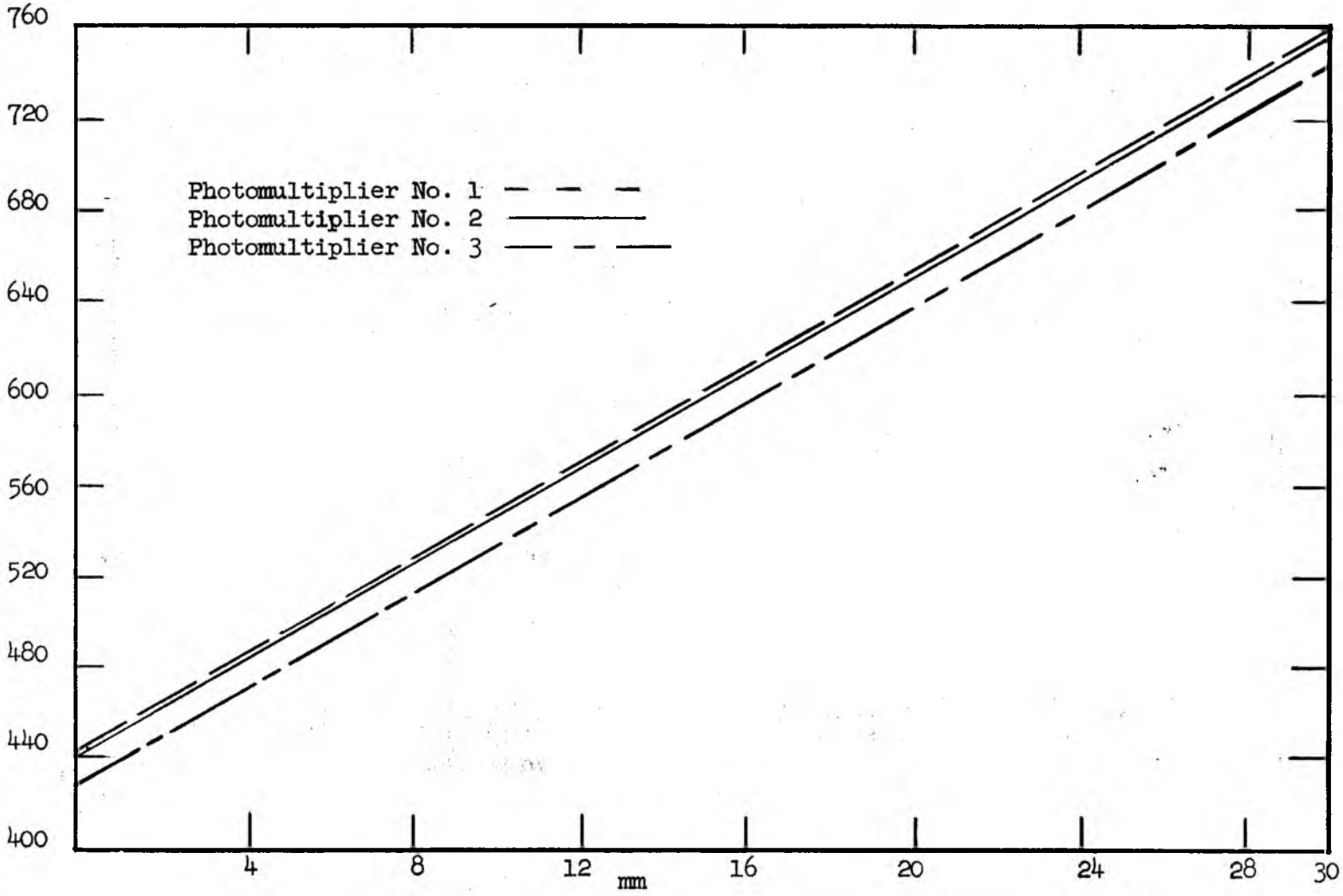

Fig. 16. Wavelength calibration in mμ corresponding to the position of each photomultiplier along the millimeter scale mounted along the focal plane of the spectrograph.

RELATIVE GAIN VS. DYNODE VOLTAGE

The relative gain of each photomultiplier as a function of dynode voltage was determined in the following manner: The light source used was a tungsten lamp. Keeping the total illumination at the cathode constant, the dynode voltage was varied in 8.6-volt steps and the output voltage recorded. To prevent errors due to saturation, the illumination was decreased by known amounts during this procedure to keep the plate current under .05 ma. The curves are shown in Figs. 17, 18, and 19.

LINEARITY OF PHOTOMULTIPLIERS

It has been assumed so far that the relation between the plate current of the photomultiplier and the cathode illumination for a given spectral distribution has been linear up to .05 ma. To check this linearity for higher values of plate current, an indirect method was used. A tungsten lamp was used as a constant source of illumination. To increase the plate current, the dynode voltage was increased. This had essentially the same effect as increasing the illumination, the increase having been determined from the output versus dynode voltage curves of Figs. 17, 18, and 19. The linearity was found to be good to within a few per cent up to a plate current of 0.3 ma, non-linearity being undetectable at and below 0.1 ma.

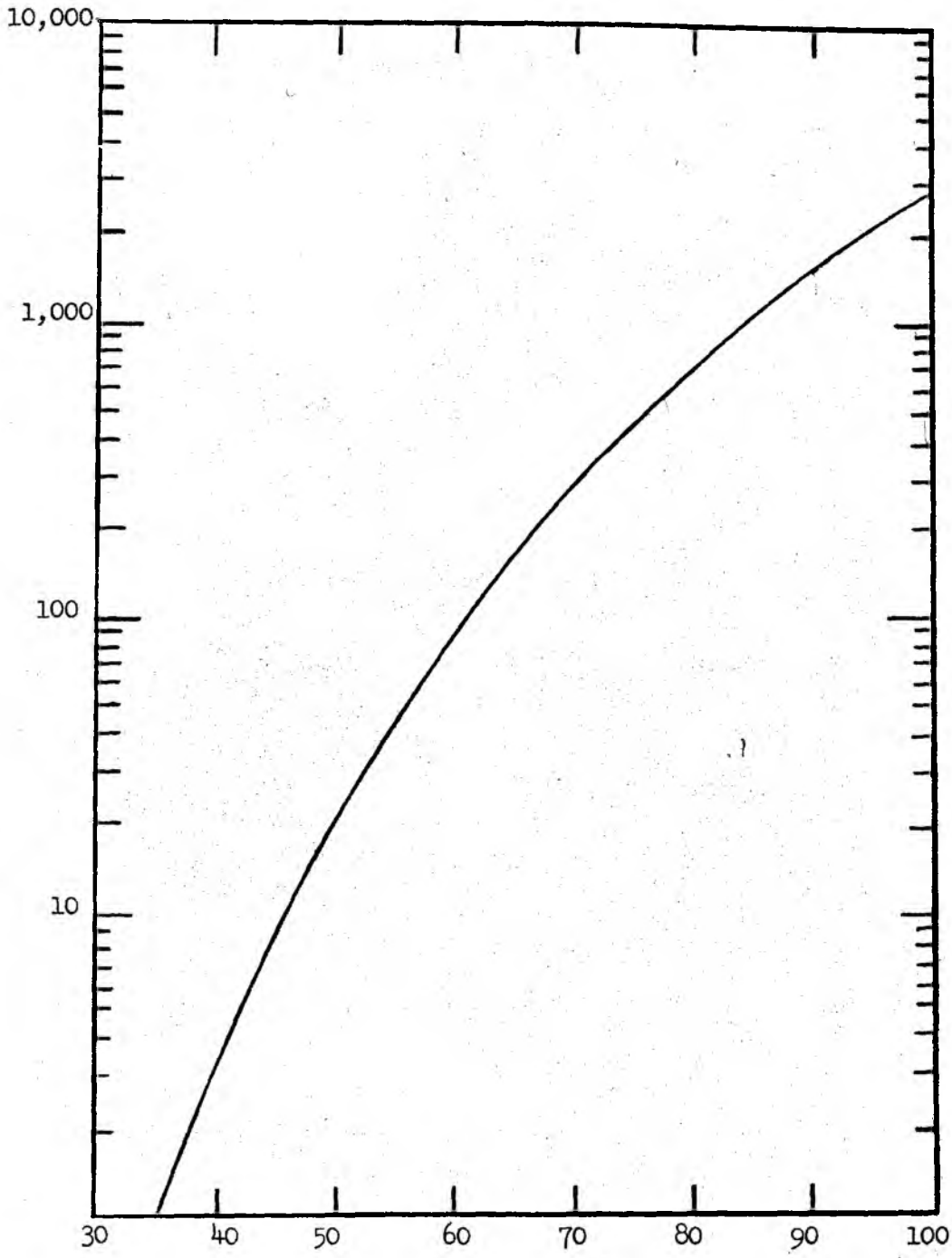

Fig. 17. Relative gain versus dynode voltage of No. 1 photomultiplier.

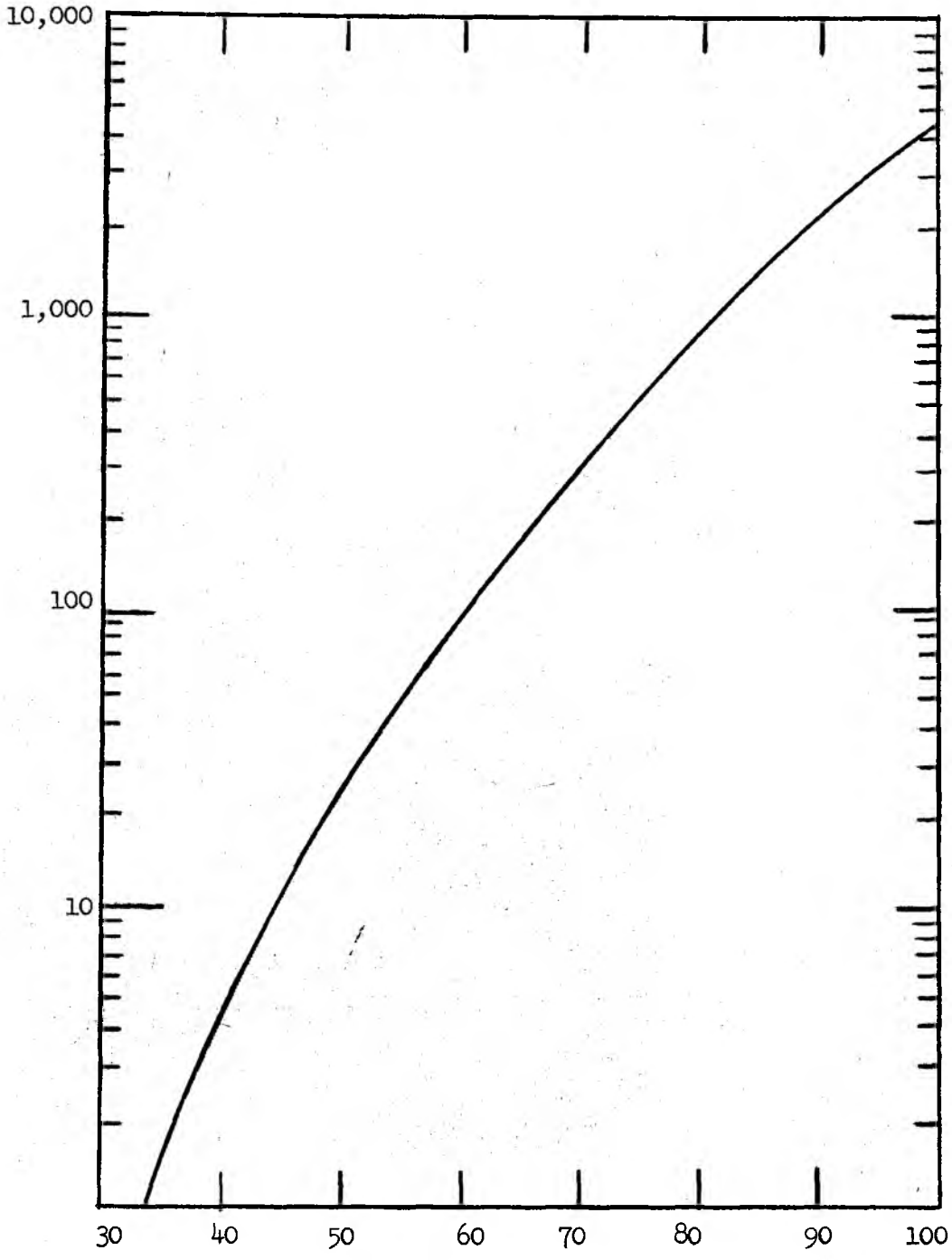

Fig. 18. Relative gain versus dynode voltage of No. 2 photomultiplier.

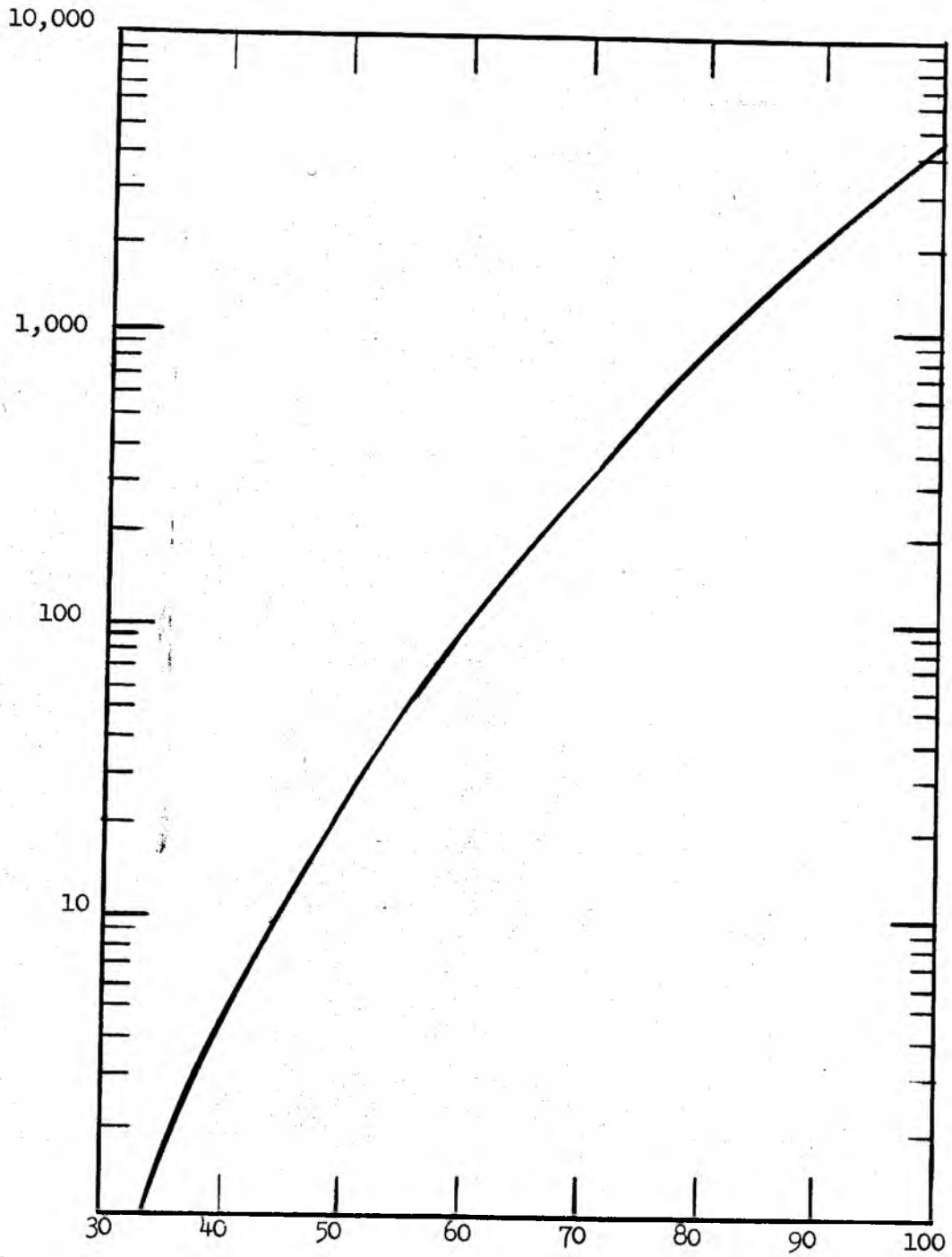

Fig. 19. Dynode voltage of No. 3 photomultiplier.

RISE TIME DETERMINATION OF PHOTOMULTIPLIERS

The rise time of each photomultiplier circuit was determined experimentally using a spark as an input signal to the cathode. The spark lasts for about 10^{-8} seconds, and can be considered for the times of interest in this work as a delta function. The decay rate of the output signal is a close measure of the RC response of the system and is equal to the rise time of the circuit. Figure 20 shows the superposition of the response of a non-saturated photomultiplier circuit to an input signal of many consecutive, similar sparks. The RC response is close to 0.2 μsec.

ABSOLUTE ILLUMINATION CALIBRATION

The sun was used as a standard light source[16] for calibration of the output voltage of the photomultipler circuit corresponding to an illumination of 1 μwatt/cm^2/mμ on the entrance slit of the spectrograph as a function of wavelength and for a standard dynode voltage of 61 volts. Sunlight was reflected by an aluminized mirror into the entrance slit of the spectrograph. The mirror was adjusted for maximum output voltage at various photomultiplier positions along the focal plane. To block out ultraviolet light transmitted in the second order of the spectrograph, a 1/2-inch plastic plate was placed over the entrance slit of the spectrograph. No correction for this plate was necessary, since this same material was used as a window in the vacuum chamber through which the impact flash light passed. The effectiveness of

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[16] Sun calibration data taken from Ralph Stair and Russell G. Johnston, Journal of Research of the National Bureau of Standards, Vol. 57, No. 4, October, 1956.

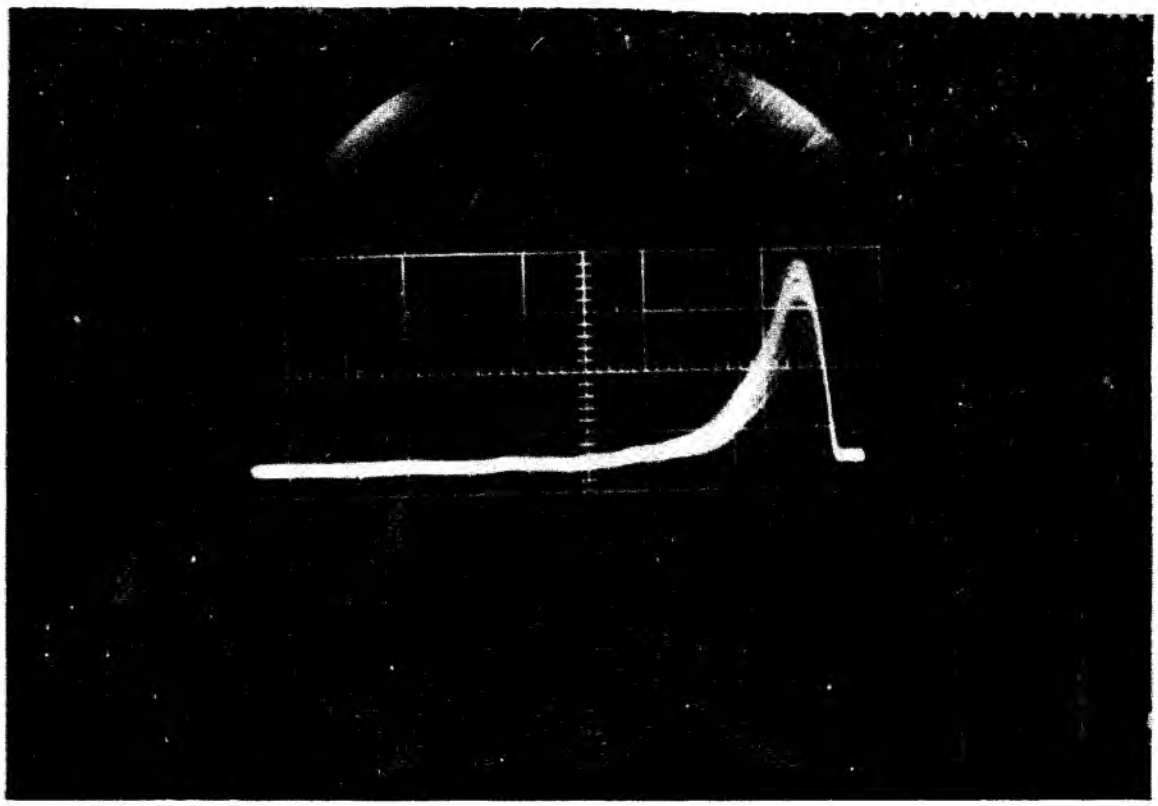

Fig. 20. Photomultiplier circuit response to a spark input signal. The voltage scale is 0.1 v/cm. The time base is 0.2 μsec/cm.

the ultraviolet filtering was observed by doubling the thickness of the plastic and observing the differences in the output voltage of the photomultipler. It was found that the transmission of the 1/2-inch plastic plate extended very slightly into the near ultraviolet. There is no detectable ultraviolet transmission at wavelengths shorter than 340 mμ. Consequently, the 1/2-inch plastic plate prevents ultraviolet contamination from the second order of the grating in the first order visible at wavelengths shorter than 680 mμ. The region of slight ultraviolet contamination coincided with the region of poor photomultipler sensitivity and was not studied in this work.

To check the calibration data from the sun, a tungsten lamp was also used in the calibration. It gave smoother and more reliable curves from point to point. The tungsten curve was fitted to the points of the sun calibration data. In this way the shape of the tungsten curve was used, not its absolute level, since it was not a standard source. Fair agreement of data appears for the two calibration methods. The curves of Fig. 21 represent the adjusted tungsten calibration. Points from the sun calibration are also shown on the graph.

The sun points representing the output voltage, V_s, as a function of wavelength for an illumination at the entrance slit of the spectrograph of 1 μwatt/cm^2/mμ for a dynode voltage of 61 volts were computed using the following equation:

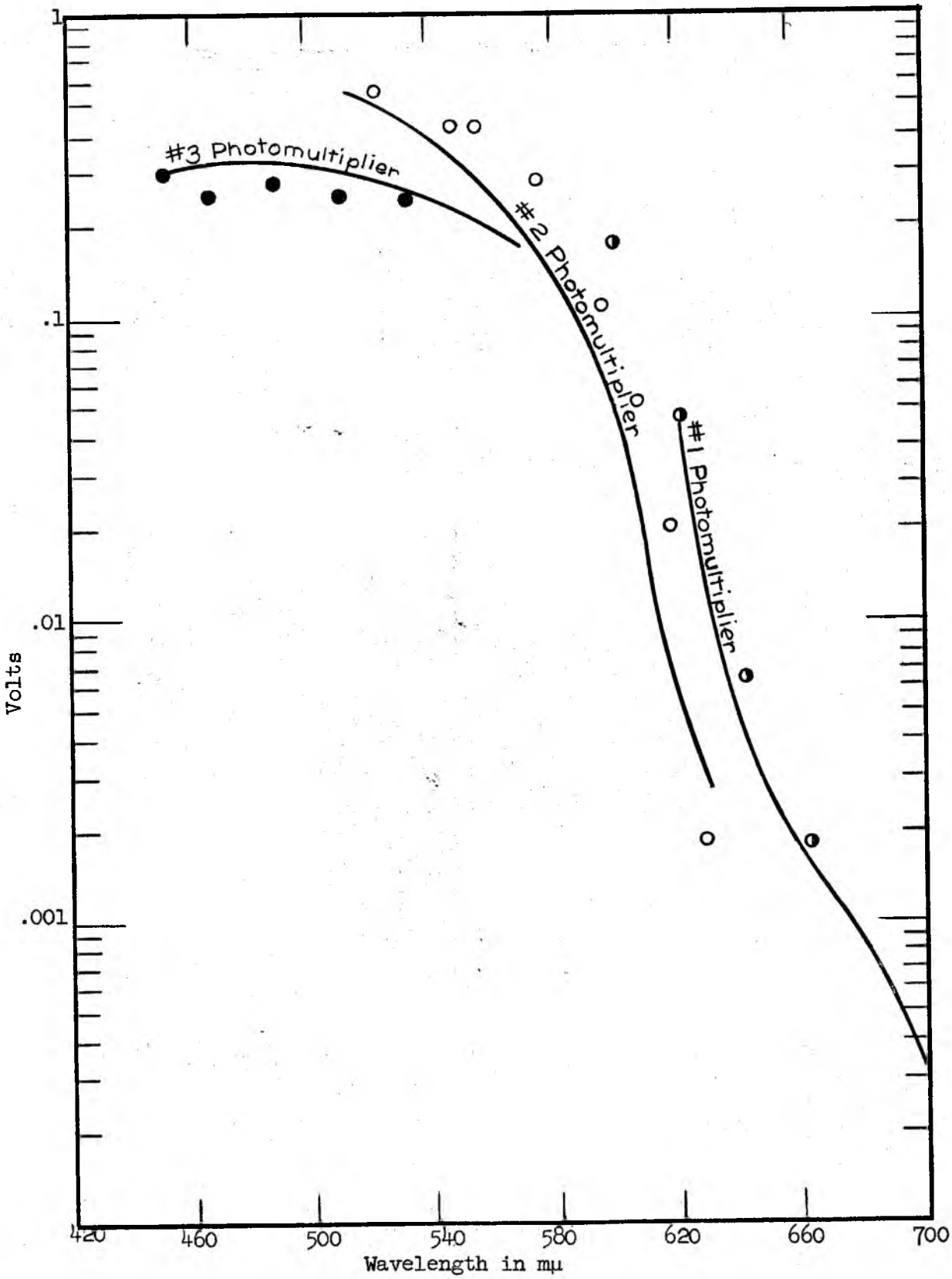

Fig. 21. Photomultiplier voltage output versus wavelength in mu for one uw per cm per mu of illumination at the entrance slit of the spectrograph. The solid lines represent the calibration curves for tungsten while the indicated points represent the absolute sun calibration. The points from the sun calibration were used to adjust the absolute level of the tungsten curves.

$$V_{s\lambda} = \frac{E_\lambda G}{W_\lambda r_\lambda G_s}$$

where E_λ = output voltage of photomultipler during the sun calibration.

W_λ = μwatt/cm^2/mμ, evaluated at λ and taken from sun tables.

G_s = gain of photomultipler at the dynode voltage used during sun calibration.

G = gain of photomultipler at standard dynode voltage of 61 volts.

r_λ = reflectivity of aluminum mirror.

The relative tungsten calibration curve was obtained in a similar manner using:

$$V_{t\lambda} = \frac{E_\lambda G}{P_\lambda G_t}$$

where P_λ = per cent of maximum height of the tungsten filament spectral distribution curve as given in the RCA tube manual.

G_t = gain of photomultipler at the dynode voltage used during tungsten source calibration.

DERIVATION OF COLLISION FACTOR

FOR MULTIPLE INELASTIC COLLISIONS

Define:

E_t = the total maximum excitation energy available to the copper atom with an initial velocity, V, after n inelastic collisions with particles at rest and having a mass of m.

E_k = the maximum excitation energy available to the copper atom received from a single, the k^{th}, collision where k varies from 1 to n.

V_k = the velocity of the copper atom after the k^{th} collision.

V_o = initial velocity of copper atom.

From Eq. (1),

$$V_k = \frac{M}{m+M} V_{k-1}$$

or $$V_k^2 = a V_{k-1}^2$$

where $$a = \left(\frac{M}{m+M}\right)^2$$

From Eq. (2),

$$E_k = \frac{Mm}{2(M+m)} V_{k-1}^2$$

$$E_t = \sum_{k=1}^{n} E_k$$

$$= \frac{Mm}{2(M+m)} \left(V_o^2 + aV_o^2 + a^2 V_o^2 + \ldots + a^{n-1} V_o^2 \right)$$

Solving

$$E_t = \frac{Mm\, V_o^2}{2(M+m)} \left[1 + \frac{a(1-a^{n-1})}{1-a} \right]$$

Define a collision factor,

$$J_n^2 = 1 + \frac{a(1-a^{n-1})}{1-a}$$

Giving,

$$E_t = \frac{MmV_o^2}{2(M+m)} J_n^2$$

Changing subscripts,

$$V_n = V_o$$

and

$$V_n = \frac{1}{J_n} \sqrt{\frac{2E_t(M+m)}{Mm}} \qquad (4)$$

where V_n now represents the miminum initial velocity of a copper atom necessary to acquire a total excitation E_t during n inelastic collisions.

J_1 equals unity, so for one collision, and dropping the subscript,

$$V = \sqrt{2E_t \frac{M+m}{Mm}} \tag{5}$$

the single collision velocity required to supply E_t.

Finally, from Eq. (4)

$$J_n V_n = V$$

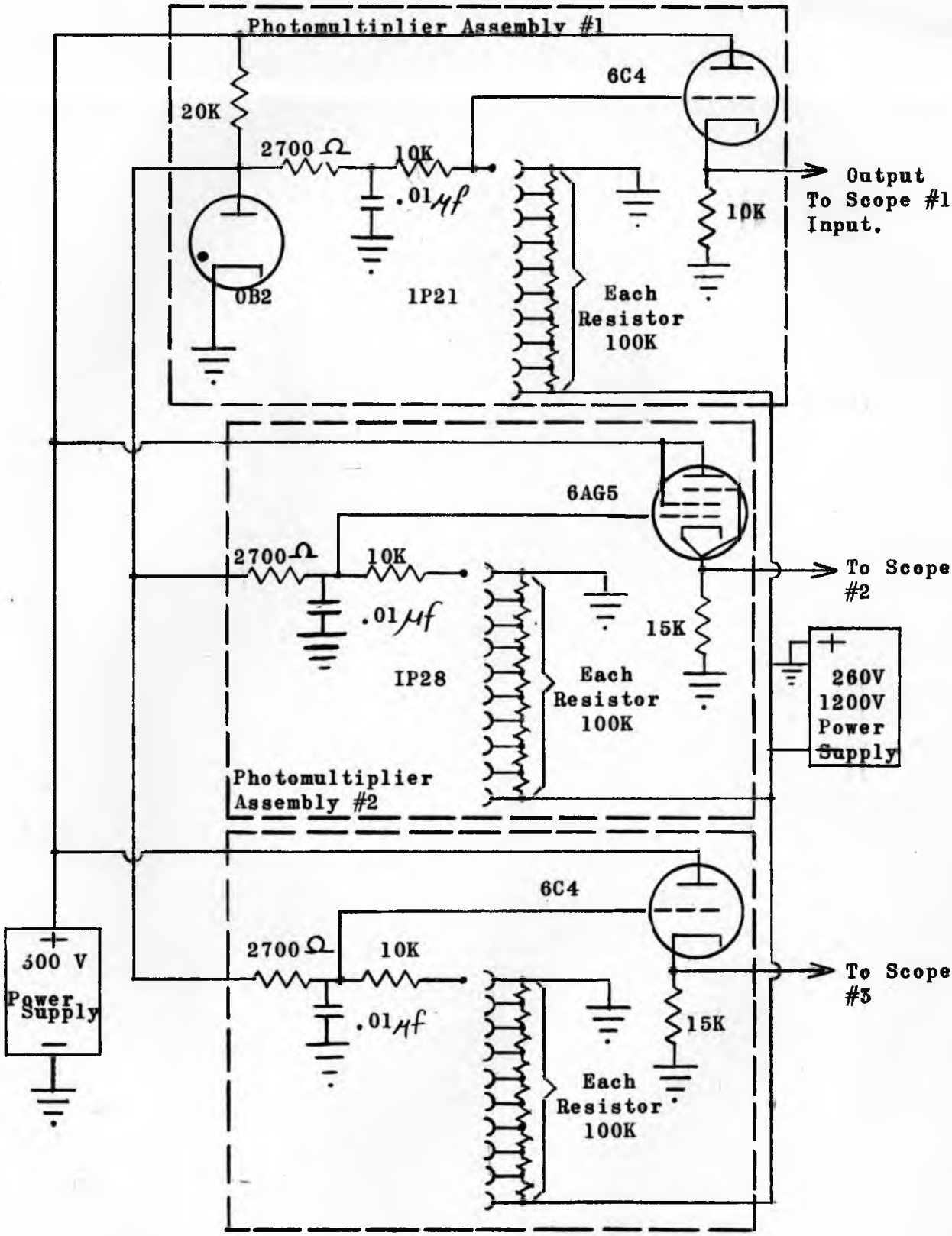

Fig. 2[illegible]. Photomultiplier Circuit Diagram.

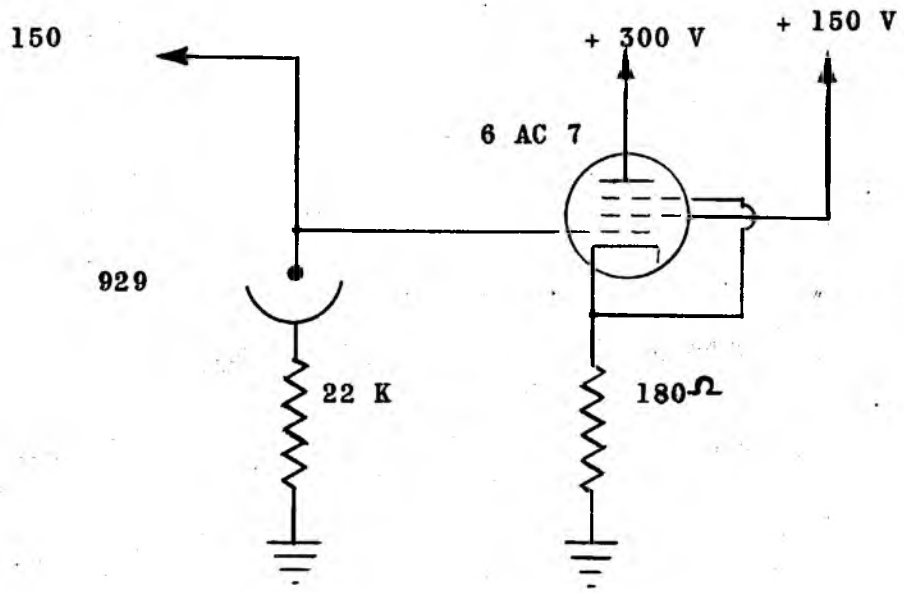

Fig. 23. Impact Viewing Circut Diagram.

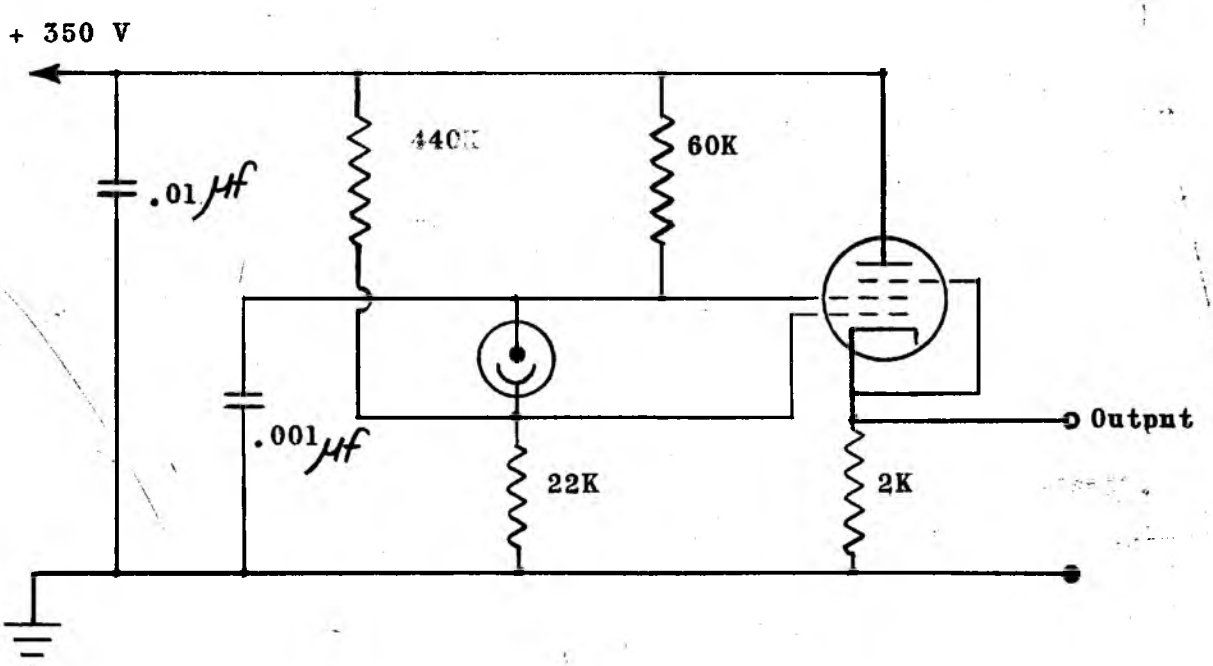

Fig. 24. Trigger Circuit Diagram.

Wavelength (mμ) \ Number of Shot	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
460								18.0			23.1						
462														16.5			
465									54.4	81.8			68.4				
475															13.6		
498				3.3	5.9	9.6											
510	466	232															
512							20.3										
560															10.5	9.0	
565			9.5	3.9	5.4	6.0											
570									99.0	163	282	123					
578	166	77.2															
582							2.6										
588														6.9			

Table 1. Data (watts/mμ) of copper-to-copper impact in argon at 6 cm of mercury pressure

Number of Shot

Wavelength (mμ)	1	2	3	4	5	6	7	8	9	10	11
451									.087	.145	.043
504		.199	.343	.151			.295				
510					.308	.427		.210			
542									.270	.290	.244
578		.346	.540			.984	.406				
585				.360	.72			.360			
630									.364	.259	.466

Table 2. Data in watts/mμ of copper-to-copper impact in one atmosphere of hydrogen

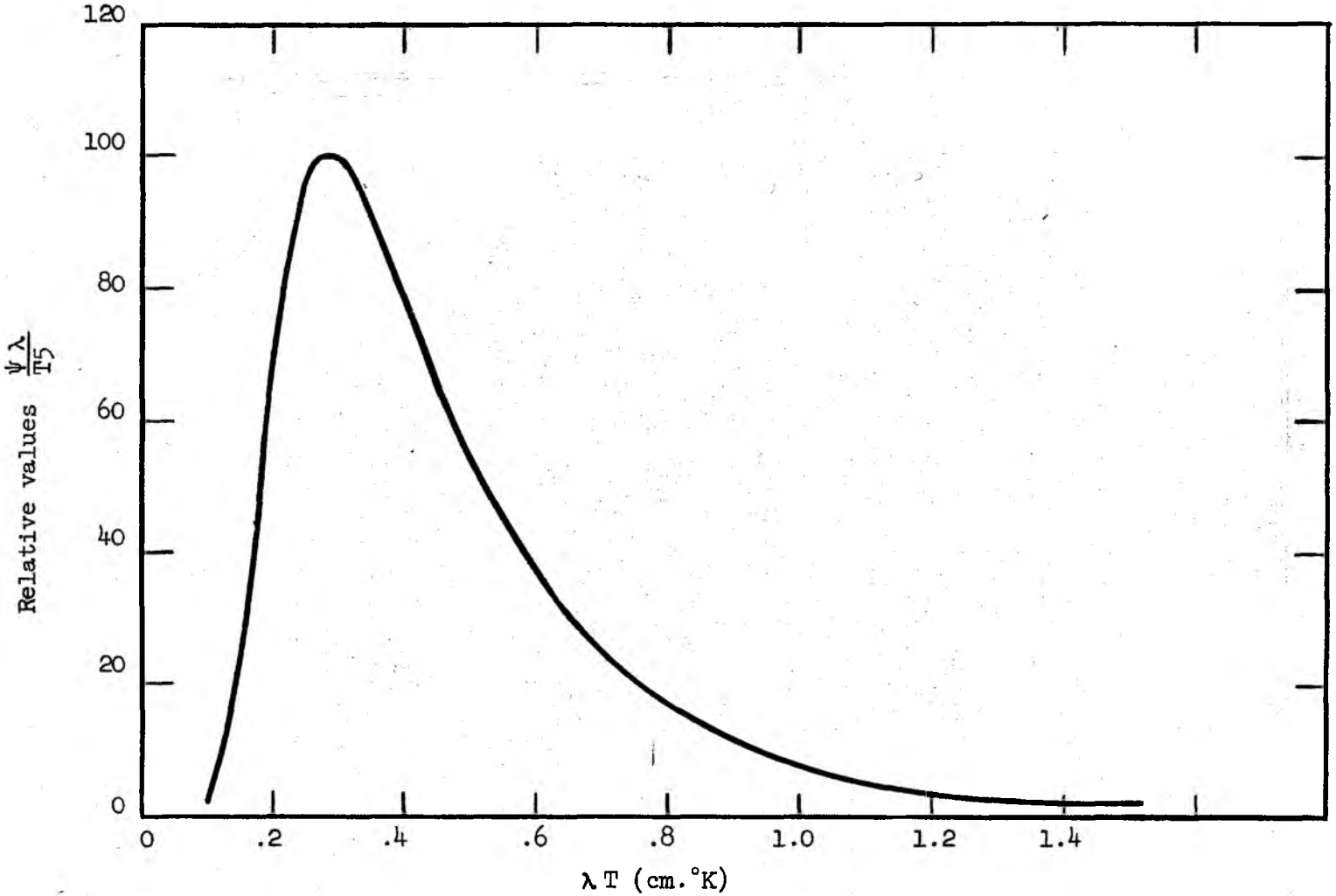

Fig. 25. Black body radiation curve.