COMPARISON OF THE EFFICIENCY OF INCOHERENT AND COHERENT LIGHT SOURCES IN A PHOTOSYNTHETIC REACTION

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ABSTRACT

A pilot experiment was performed to compare the photosynthetic effect of a coherent laser beam with that of a noncoherent monochromatic beam at the same frequency and power level. Two different results were obtained with different filters and power levels. In both cases the laser effect was greater: in one it was approximately 30 times greater; in the other, about twice. An attempt is made to explain the discrepancy in terms of various factors that could have been responsible; the possibility of molecular resonances or some unknown effects is also discussed briefly.

I. GENERAL CONSIDERATIONS

The factors that lead a researcher to a hypothesis depend on his experience, his intuition, as well as on careful observations of experimental data and on a study of the results of others. A hypothesis has to be verified by an experiment that either confirms the proposed hypothesis or guides attention to a different chain of reasoning.

On reviewing the literature of biological applications of the laser, and more specifically of laser-irradiated media, one invariably runs across the frequency dependence of the power absorption or extinction factors of the irradiated materials. As an example, Rounds notes the wavelength specificity of laser-induced biological damage in such cultures as human glioblastoma cells, abdominal wall of a rat, and a riboflavin solution.[1]

As one approach, one might seek a correlation between the frequency dependence and the geometrical characteristics of the biological particles in a manner suggested by the properties of microwave artificial dielectrics.[2,3] This approach is also related to that of Saito and Schwan, who related wavelength absorbance of organic particles to their geometrical and configurational properties.[4] However, the available data are too sparse at this juncture to permit the derivation of a relationship between the laser wavelength and the geometrical properties of the particles. Not only are laser irradiations restricted to a few discrete wavelengths, but any biological sample also comprises a large number of variables that cannot be accounted for by any simple hypothesis; many of them are not yet clearly understood by the biologist.

A more fruitful approach is the experimental one. Based on work done under the supervision of Prof. Lester Packer at the U. C. Department of Physiology-Anatomy by Richard Norman on the effect of laser irradiation on the photosynthesis of sea ulva, a type of seaweed that grows in San Francisco Bay, we undertook the measurements described in the present report.

Before describing the experiment, we shall give a brief account of the frequency dependence of energy absorption by a suspension of biological particles in a cell or of cells in a tissue, in a treatment similar to that of absorption and scattering in the colloidal sciences.

A. DIELECTRIC ABSORPTION

The absorption of radiation in biological material (treated as a dielectric medium) has been described by Schwan, who found the dependence of the dielectric constant frequency up to the gigacycle region.[3] The dielectric constant of muscular tissue, for instance, decreases with frequency and there are three step decreases corresponding to three relaxation frequencies of the medium.

B. SCATTERING

Scattering occurs when the electromagnetic wave passes between two regions of different indexes of refraction; e.g., a suspension of spherical particles in a medium. The phenomenon can be viewed in various ways, as follows.

1. RALEIGH THEORY. Lord Raleigh[5] made studies of scattering for the case when the radiation wavelength λ is much larger than the particle dimension r . He found the intensity of absorption to be

$$S = 24\,\pi^3 \left(\frac{m^2 - 1}{m^2 + 1}\right)^2 \frac{V^2}{\lambda^4} \tag{1}$$

where S is the intensity per unit area

V is the volume of the particle (a sphere)

m is the normalized index of refraction, i.e., the ratio of the index of the particle to that of the medium

This equation tells us that $S \sim 1/\lambda^4$, which accounts for the blue (wavelength) scattered by the ionosphere giving the characteristic color to the sky.

2. THE MIE THEORY. The dipole model of Raleigh with which he derived his equation does not hold for large particles, with dimensions of the order of the wavelength $(\lambda \approx r)$. Here electric moments of higher orders and induced magnetic moments must be taken into consideration. This work was done by Mie[6] around 1908, when he derived his equation for the scattered intensity:

$$S = \frac{\lambda^2}{2\pi} \quad \frac{a_\nu^2 + P_\nu^2}{2\nu + 1} \tag{2}$$

where a_ν and P_ν are functions of $\alpha = 2\pi r/\lambda$ and $\beta = 2\pi rm/\lambda$ (of Eq. 1). A scattering coefficient K is also defined: $K \equiv S/\pi r^2$.

3. THE EFFECT OF PARTICLE CONCENTRATION. Close packing of particles has many effects, notably multiple scattering. One method of dealing with bulk effects on the index of refraction is that proposed by Bateman et al.:[7]

$$n_2 = n_1 + \Delta n_{12}/\varphi_2 \tag{3}$$

where n_2 = apparent index of refraction of suspended particles
n_1 = index of refraction of the solution
φ_2 = concentration or volume ratio of the medium
Δn_{12} is defined as $\Delta n_{12} \equiv n_{12} - n_1$ where $n_{12} = \varphi_1 n_1 + \varphi_2 n_2$
and the subscripts 1,2 denote medium and particle, respectively.
Also, $\varphi_1 + \varphi_2 = 1$.

C. POSSIBLE ALTERNATIVES

Several experiments suggest themselves besides the one selected. Some of them are briefly mentioned below.

1. TUNABLE LASER. It would be highly desirable to develop a laser tunable over an appreciable frequency range. Such a device would permit

a complete spectroscopic study of laser radiation on organic systems.

Dr. S. E. Harris at Stanford University and Dr. L. W. Davis in Berkeley have worked on this problem, but no such device could be made available in time for the present project.

2. MEASUREMENTS AT VARIOUS DISCRETE FREQUENCIES. Irradiation of tissue cultures or a mitochondria suspension at various frequencies could be a useful procedure owing to the regular geometric properties and internal structure; the results could be compared with these obtained from irradiating a nonbiological suspension or colloidal solution of the type used in experiments in physical chemistry, in which chemical processes can be ruled out and other physical parameters could be controlled and isolated (e.g., density, concentration, size, dielectric constant, etc.).

Simulation of a biological system by a colloidal system suggests itself because the proteins which are major constituents of the former system occur mainly in the colloidal size range (1-100 mμ). This size range has the property of large surface-to-charge ratio which gives rise to important electronic processes in the biological systems.

3. POLARIZATION. Another approach might be the study of the effect of polarization on the configurational distribution of the particles in a medium. In such an experiment, center of symmetry, geometrical axis, and other such characteristic parameters are selected for study.

4. OPHTHALMIC EXPERIMENTS. Still another approach might be the study of the effect of laser irradiation on retinal rods and cones, which are sensitive to light at specific frequencies, as well as other pigments and biological constituents whose natural function is to enhance radiation absorption at certain frequencies.

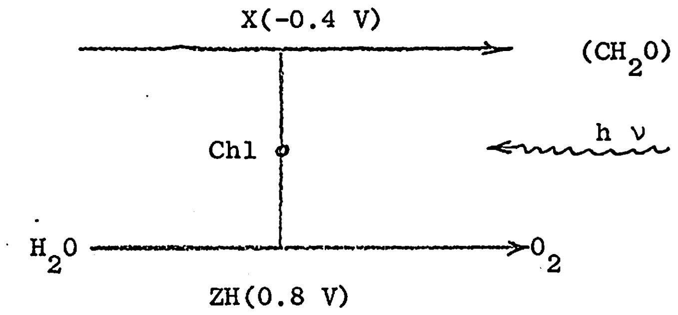
II. DESCRIPTION OF THE EXPERIMENT

A. GENERAL

Photosynthesis of green plants is the process by which plant cells in the presence of chlorophyll utilize the energy of light radiation to form glucose. The process is represented by the following chemical reaction:

$$6CO_2 + 6H_2O \xrightarrow{\text{photons}} 6O_2 + C_6H_{12}O_6$$

More specifically, photosynthesis is a tripartite process, as indicated schematically in the following diagram.



The first two processes are "dark" enzymatic processes, occurring at approximately constant level of energy; the third is an energy-accumulating photochemical process. This latter must be an oxidation-reduction--either hydrogen atom transfer, or electron transfer, or a combination of both. This transfer goes from a donor, ZH (an intermediate in the lower enzymatic reaction chain), with a high oxidation potential (about 0.8 Volt), to an acceptor (an intermediate in the upper enzymatic reaction chain) with a high reduction potential (approximately -0.4 Volt). The process thus leads to the storage of about 1.2 eV of chemical energy per electron (or hydrogen atom) transferred. Since the reduction of carbon dioxide to the carbohydrate level requires the transfer of four hydrogen atoms, the total energy storage in the reduction of one carbon dioxide molecule is 4.8 eV or about 110 Kcal/mole. Energy storage in a form other than oxidation-reduction energy can play only an auxiliary role in photosynthesis; this applies, in particular, to the formation of high-energy phosphate (ATP).

B. THE EXPERIMENT

A comparison between a laser beam and a beam from an ordinary light source can be made on the basis of power level and frequency; but the light from an incandescent source is not coherent. Thus if each beam is used to bring about a chemical reaction, the differences in the result should be assignable to the coherency, or else some unknown property of the laser beam.

The photosynthetic process is an obvious candidate for such an experiment because of its sensitivity to light and the easy measurement of oxygen evolution by an oxygen electrode.

The plant used was a marine algae of the genus ulva. An He-Ne laser was used because of its ready availability in a relatively low-power version (to avoid hazards), although its frequency, 6328 Å, is not ideal, since it happens to be on a slope in the action spectrum curve of Ulva.

C. METHOD AND EQUIPMENT USED

The experiment set up was built as shown in Fig. 1. The beam from the He-Ne laser A (LAS 101, Electro-Optics Associates, 6328 Å) was passed through a diverging lens system B (16-mm Excessulite, 2 in., f/1·6 ELC, Bell & Howell) and reflected by a prism C. A shutter permitted the exposure of an Ulva sample D to the beam. The sample was placed in a Lucite cup E (1-in. diam., 3/4 in. deep), submerged in salt water and covered by the oxygen electrode F, a detailed description of which appears in Appendix A. The electrode was filled with a KCl solution and covered with a polyethylene membrane. A power meter G (Model 610, Optics Technology, frequency characteristics appear in Appendix B) was used to measure the brightness of the light spot by direct exposure to the site of the sample, before placing the sample in its position. Upon the exposure of the Ulva to the laser light, a recorder H (Graphic Recorder, Model G14, Varian Associates) was used to record the oxygen evolution.

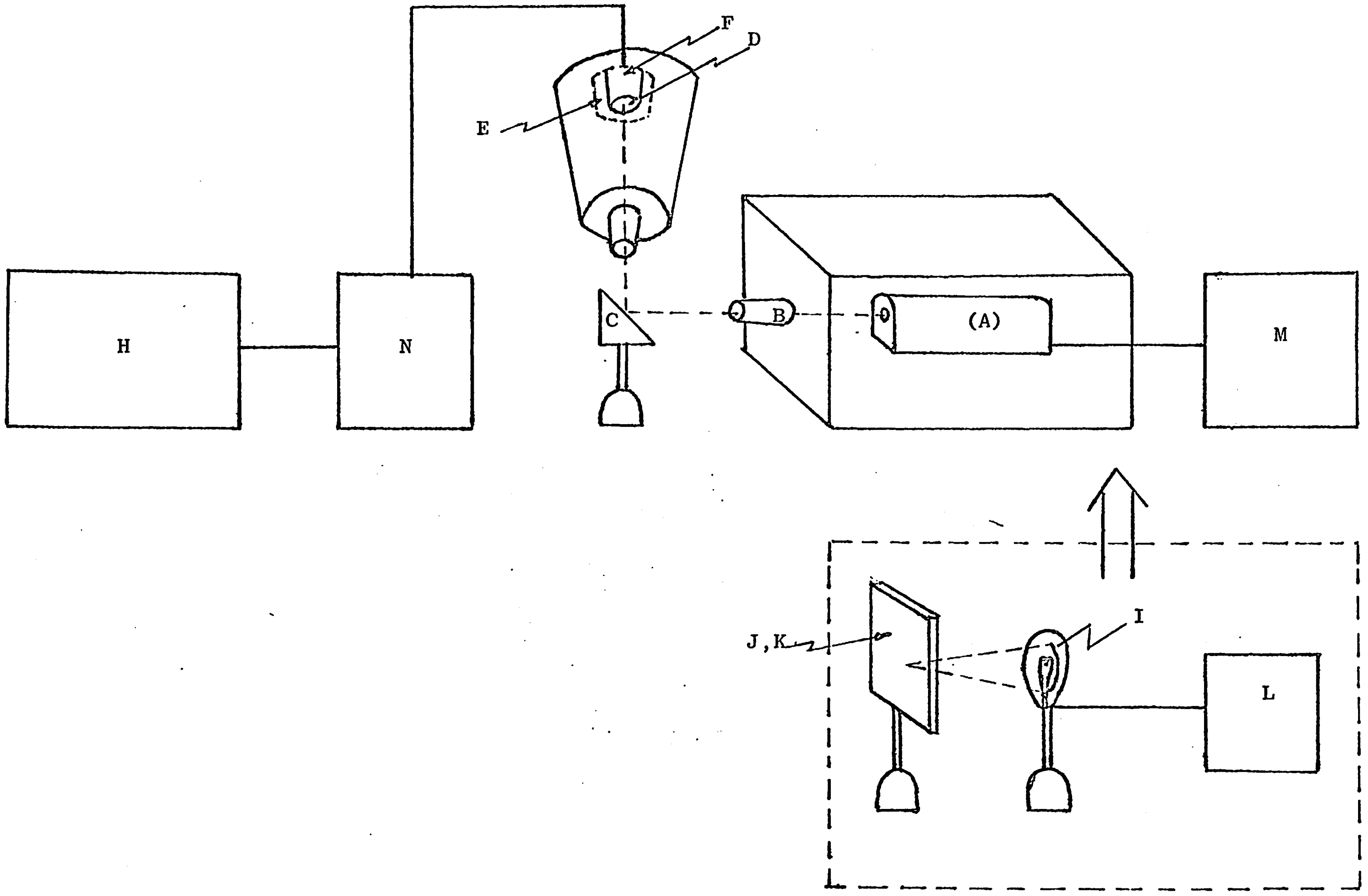


FIG. 1.--Experimental arrangement.

The laser was then removed from the box and a tungsten lamp, light source I (150 watt, 115 V ac) was installed in its place. Two sets of filters J (Corning frequency filters 1-58 and 2-62, whose frequency characteristics appear in App. C) and K (LCU transmission filter, peak at 6299 Å, frequency characteristics are given in App. D) were used in two subsequent experiments. The power of the transmitted beam was measured and adjusted by a variable autotransformer L to the level of the laser beam power. Again the results of the photosynthesis were recorded.

D. RESULTS

The recorded plots of the two experiments appear in Fig. 2 (photosynthetic effect as a function of time). The two plots in Fig. 2(a) represent the oxygen evolution in the first experiment using (1) the LCU filter in conjunction with the tungsten light, and (2) the laser beam, at equal power levels of 0.06 mW. The two plots in Fig. 2(b) represent the oxygen evolution in the second experiment for the incandescent tungsten light filtered through the Corning filters and the coherent laser beam, at equal power levels of 0.6 mW. In each case, laser light produced a greater photosynthetic effect than incandescent light at the same frequency. In the first experiment, at 0.06 mW, the effect was about 30 times stronger; in the second, at 0.6 mW, about 2 times stronger.

To allow for errors owing to the frequency responses of the light power meter, the glass filters, and the Ulva (action spectrum with constant input power), the following calculation was carried out on the data collected from the corresponding graphs (see App. E). The responses of the several components are tabulated and multiplied together to obtain the over-all response.

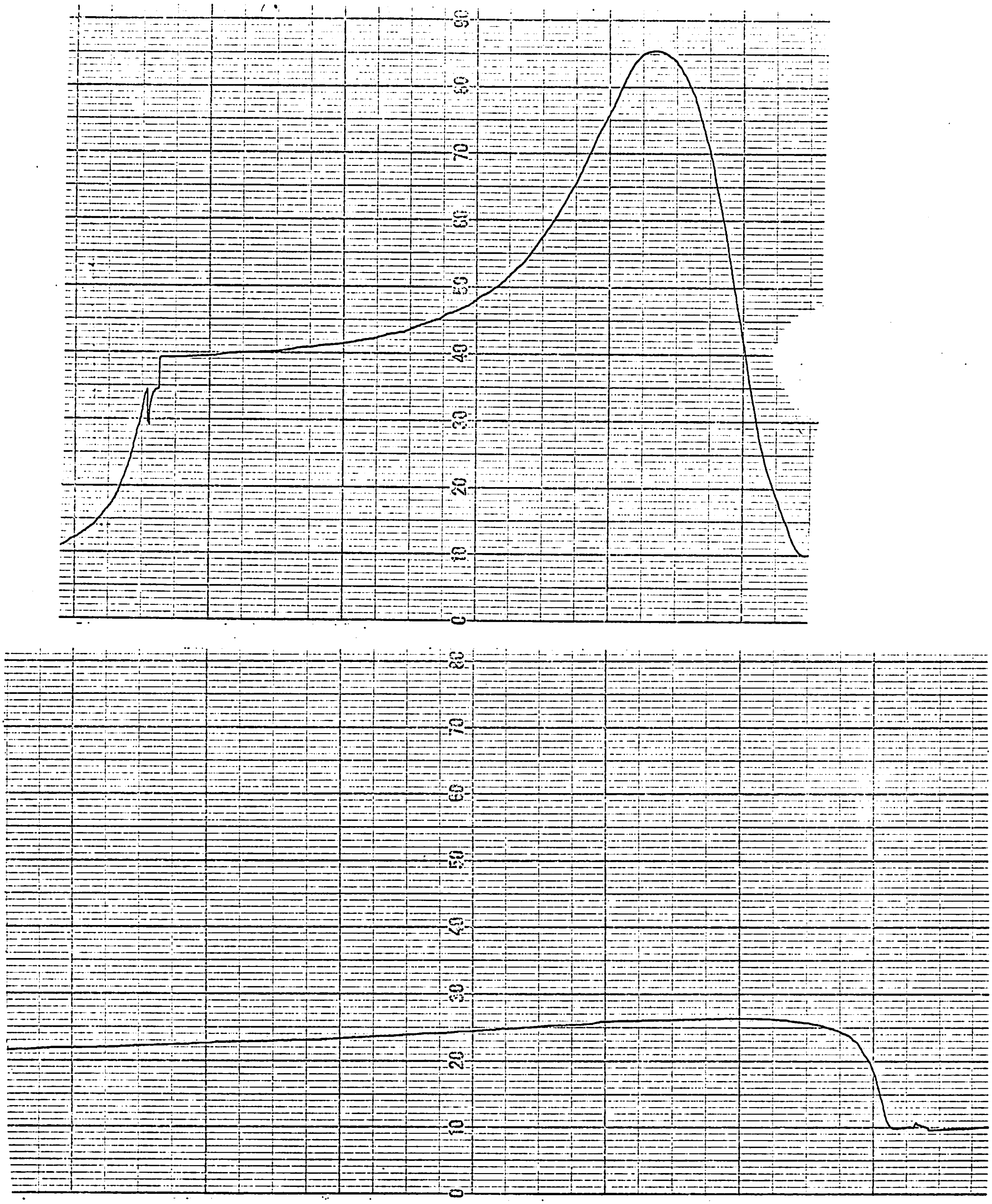


FIG. 2(a).--Photosynthesis (raw data) with laser (top) and noncoherent beam at o.06 mW input (1-mV scale). Time progresses from right to left.

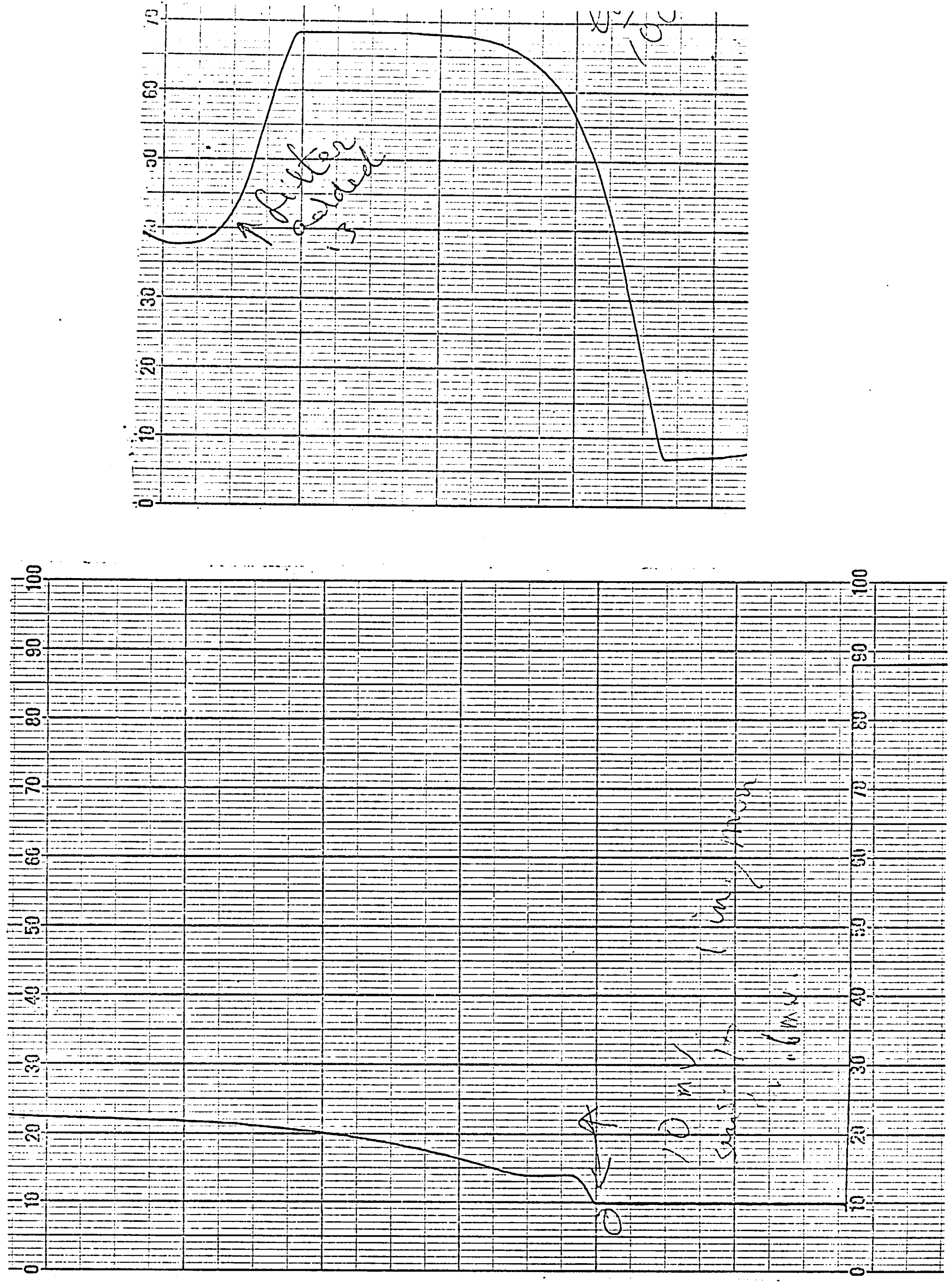


FIG. 2(b).--Photosynthesis (raw data) with laser (top) and noncoherent light at 0.6 mW input (top at 100-mV scale, bottom at 10-mV scale). Time progresses from right to left.

TABLE 1.--Relative responses of experimental components, first experiment.

Wavelength (mμ)	550	580	610	625	632.8	640	670	700
Responses								
Meter	0.8	0.87	0.96	1.00	1.00	1.00	1.07	1.13
LCU filter	0	0.033	0.165	0.5	1.00	0.495	0.033	0
Ulva action spectrum	16	25	31	37	35	41	65	0
Response product	0	7.2	49	185	350	205	23	0

The product of the relative responses is plotted in Fig. 3. In order to compare the intensity of the incandescent light (which radiates over the range of frequencies shown in the tables) with that of the laser, the total radiation is calculated from the over-all response curve and normalized at the laser frequency. The area under the curve is calculated as shown and divided by the area for a laser frequency to obtain the ratio R .

The ratio is R = 4881/5900 = 0.83 , which means that for the same measured power at the sample, the result for the laser must be decreased by 17% before it can be compared with the result for the incandescent light.

A similar correction was carried out for the second experiment. The data are tabulated in Table 2.

TABLE 2.--Relative responses of experimental components, second experiment.

Wavelength (mμ)	590	600	610	620	640	670	690	700
Responses								
Meter	0.91	0.92	0.94	0.96	1.00	1.05	1.12	1.1
Corning filters (1-57 & 2-62)	0	0.22	0.55	0.78	.88	0.6	0.32	0.32
Ulva action spectrum	30	30	30	32	41	62	35	0
Response product	0	58	154	234	360	390	113	0

Here R = 14370/21500 = 0.67 .

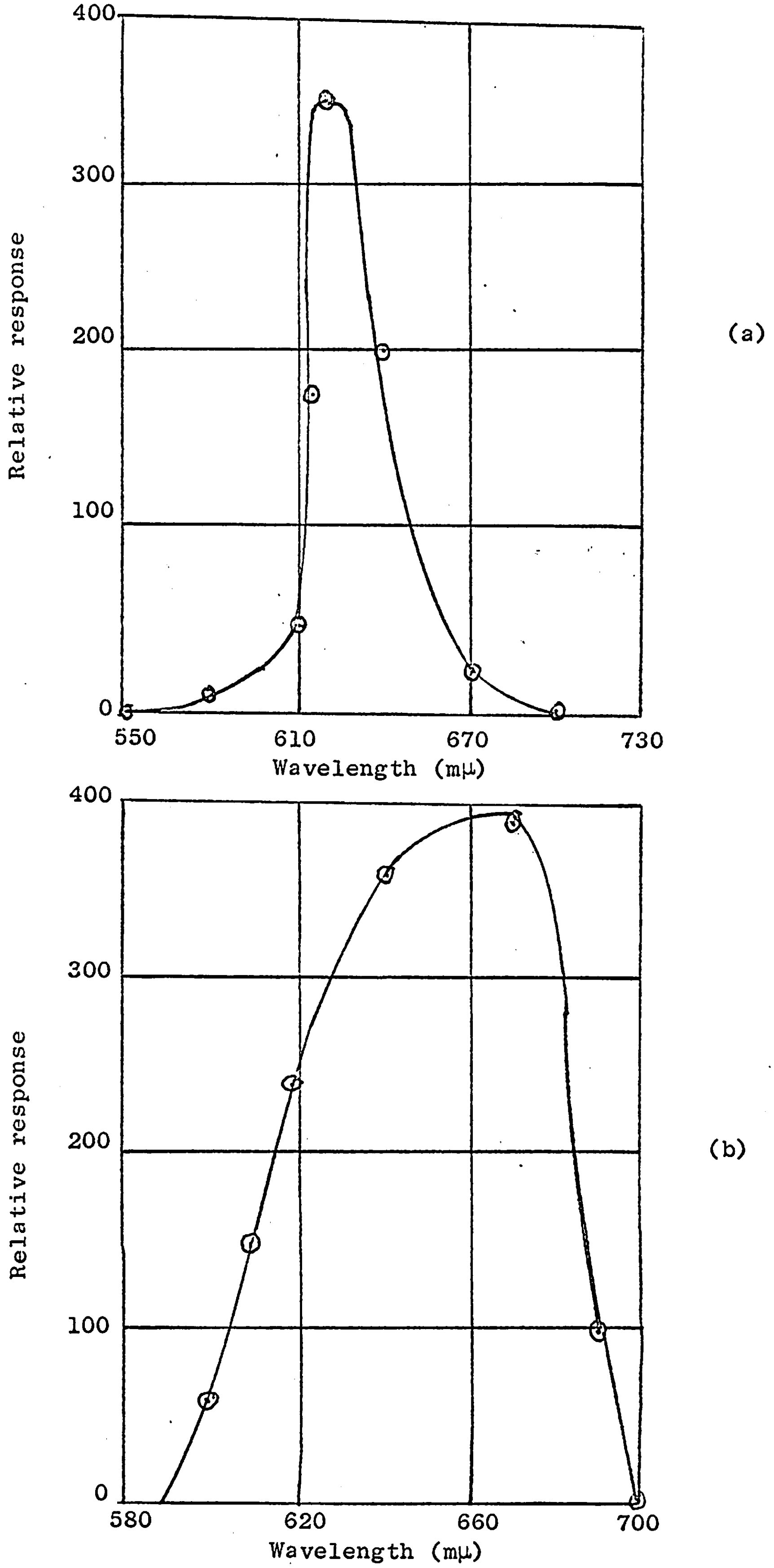


FIG. 3.--Relative response of experimental components: (a) first experiment; (b) second experiment.

To make the comparison, the curves of Fig. 2 were examined to determine two values: a maximum (usually near the beginning of the experiment) and a minimum evolution of oxygen to which the curve tends asymptotically after several minutes. (Not all the curves are similar: some remain steady and others exhibit oscillations, as mentioned below.) If we designate the maximum and minimum ratios of voltage measured with laser irradiation to that measured under incoherent irradiation by r_{max} and r_{min}, respectively, we obtain, after correction by the ratio R derived above,

$r_{max} = (7.5/1.6)\ 0.83 = 2.75$ and $r_{min} = (2.75/1.00)0.83 = 2.3$ (first experiment)

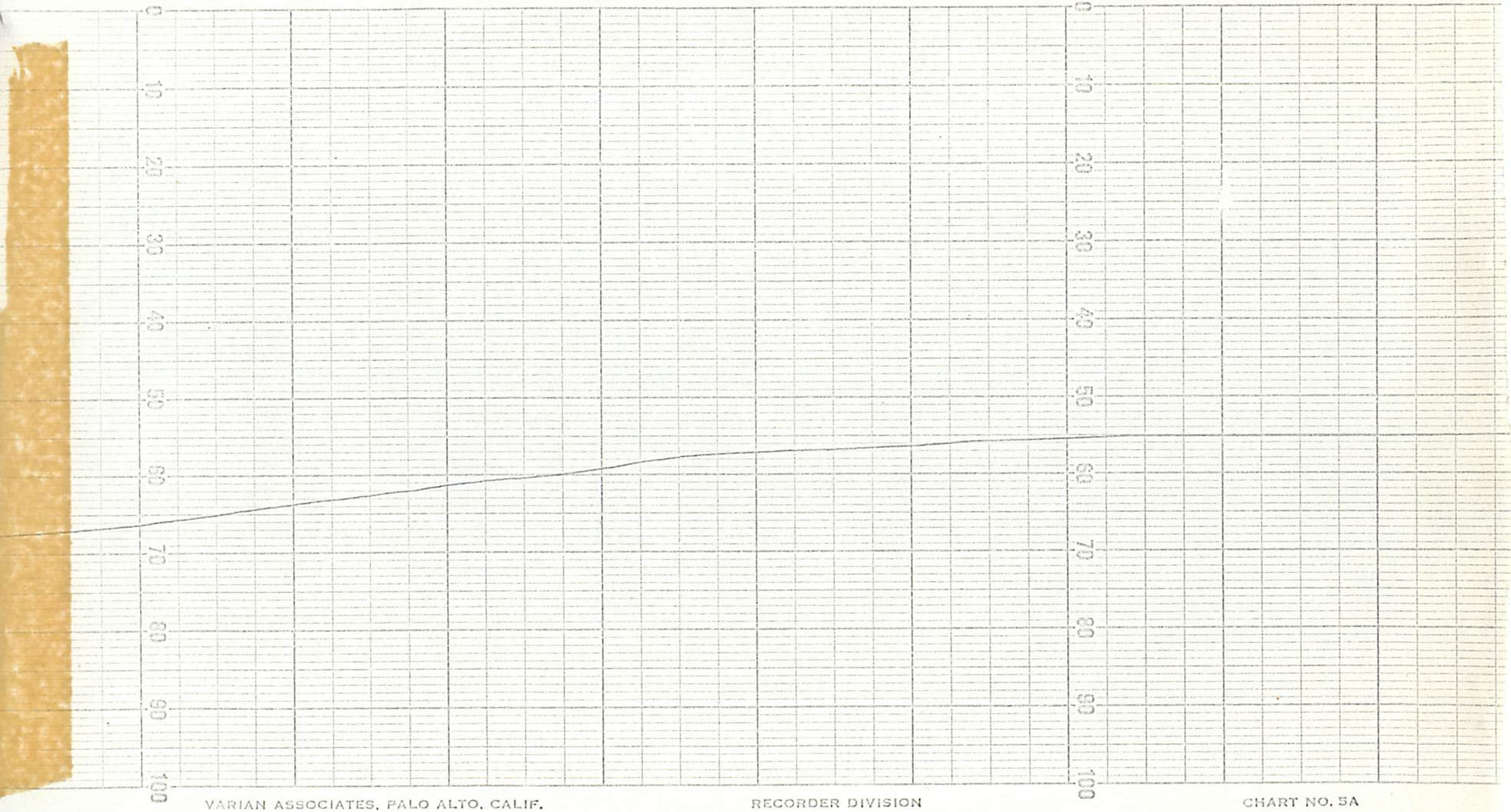
$r_{max} = r_{min} = (610/13)0.67 = 32$ (second experiment)

The first of these results is derived from the curves of Fig. 2(a); the second, from the curves of Fig. 2(b), which exhibited no discernible minima. It should be noted that not all the experiments in the present series were always exactly reproducible. For instance, at the higher power levels of the sort associated with the second experiment, some runs yielded oscillations (Fig. 4). Such oscillations are known to laboratory workers, but their cause is not entirely understood. In the present series, such results were excluded.

III. DISCUSSION

A. DISCREPANCIES

The discrepancy between the results of the first and second experiments cannot be explained on purely physical grounds. In each case, coherent light yielded a stronger effect. The two experiments were essentially identical, except for the following features: one was carried out at 0.6 mW in July, the other at 0.06 mW in November; and slightly different filters were used for the incandescent lights in the two cases. However, all measurements were compared within minutes of each other at one power level, and on another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RECORDER DIVISION
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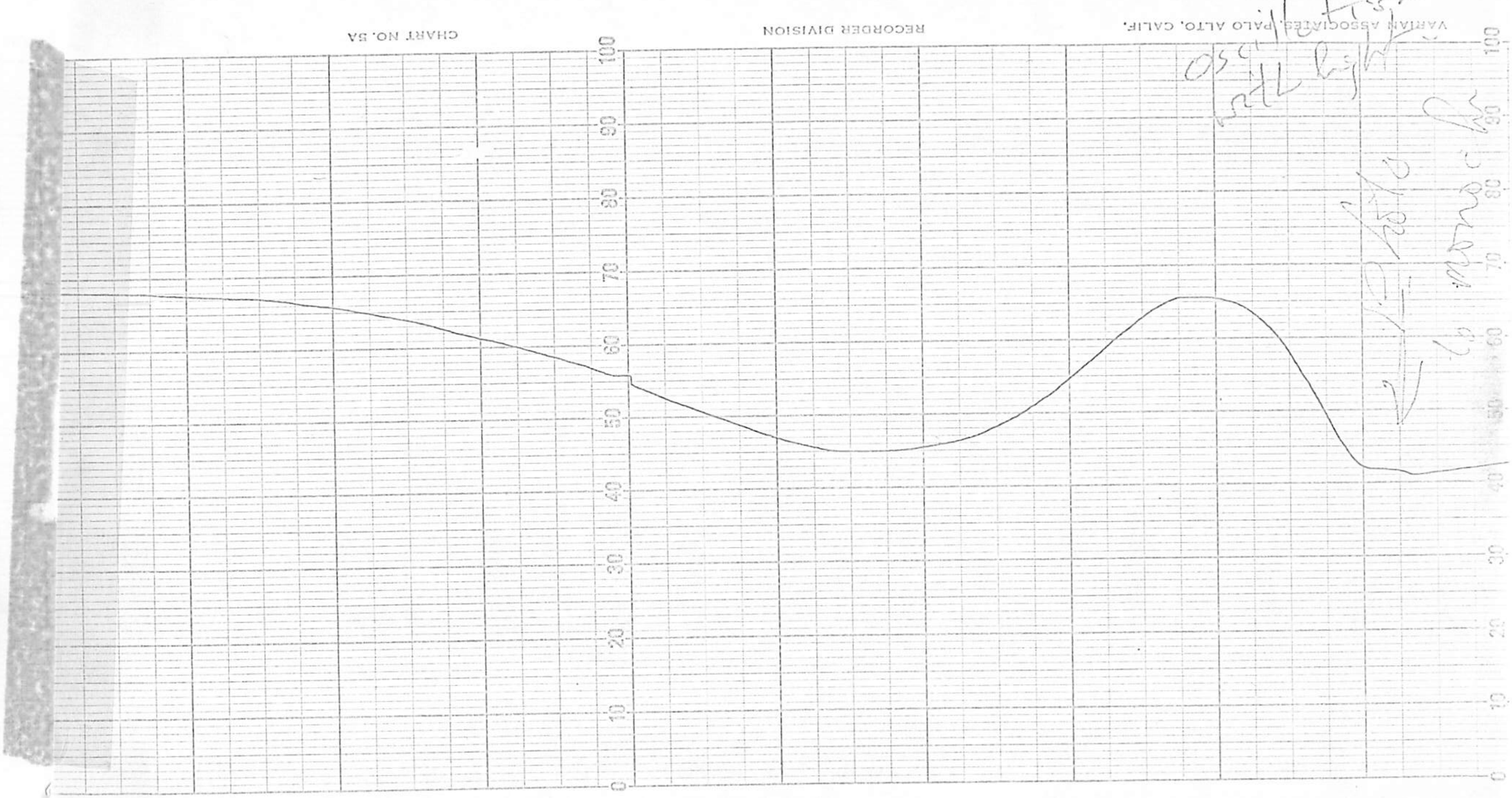

FIG. 4.--Oscillatory response in photosynthesis of Ulva on exposure to noncoherent light (raw data). Initial response period is of the order of several minutes. Time progresses from right to left.

sample at another power level later in the season. The only physical discrepancy is that different filters were used on the lamp on the two occasions. The difference between the effects of the two filters (Tables 1 and 2) is that the filter used in the low-power experiment (which yielded the lower ratio between laser and lamp results) is narrower; however, that effect should be taken care of in the calculation of the correction ratio R .

Theoretically, the values of the corrected ratios should be unity, i.e., photosynthesis with coherent and incoherent beams should be the same. As shown, optical errors may account for a small factor of the error. Other possible factors are the following.

(1) In our correction for errors due to the relatively large bandwidth of the filters versus the very selective frequency of the laser, we summed up areas under all the band frequencies. This procedure assumes a linear dependence of oxygen evolution on the input power. But is this assumption justified? In the range under consideration, it is; the curve of photosynthetic effect vs light intensity is substantially linear[8] and deviations from linearity would account for a relatively small error that could be computed, with some effort, by making a correction at each frequency under consideration.

(2) The presence of the transients in the first experiment may be a factor. Transients as a function of time (e.g., Fig. 2a) have been observed by other experimenters on algae when treated with monochromatic light.[9] However, such transients are not exactly identifiable with those observed in the present experiment.[10]

(3) Chloroplasts, which play a major role in photosynthesis, have an extremely orderly fine structure as viewed by the electron microscope, and exhibit certain physiochemical properties that are responsible for dimerism, adsorption, and dichroism (polarized absorption) in the chlorophyll molecules.[11] Thus resonance effects, frequency dependences, and light-induced changes might be responsible to a certain extent for the results of our experiment.

(4) Various Ulva samples gave widely differing responses, including frequent oscillations (Fig. 4); this fact makes it difficult to state definite ratios between the results of coherent and noncoherent irradiations; moreover, the response differs over various areas of the sample itself and the oxygen evolution also varies with time.

B. LIMITS OF THE METHOD

We should like to discuss here possible experimental errors and the extent to which they were controlled in the present experiment.

(1) Optical difficulties were encountered in obtaining two beams (laser and ordinary light) identical in area and homogeneous in brightness. Nevertheless, good accuracy with the equipment described in Sec. II-C was achieved.

(2) The input power from the laser beam and from the light source was essentially constant, with variations not detectable over short periods.

(3) Artifacts of the experiment yielding a signal when no photosynthesis was taking place were ruled out by calibration experiments with a dead sample. The reading was zero.

(4) Instabilities of the recording instrument were ruled out by permitting a long warm-up period and checking the baseline frequently by turning off all light sources.

IV. SUGGESTIONS AND RECOMMENDATIONS FOR FUTURE WORK

For the general area of biological experimentation with the laser, some suggestions are given in Sec. I-C.

For the specific study of Ulva photosynthesis with laser light, the following suggestions come to mind.

A. EXPERIMENTS WITH THE LASER

(1) Using a frequency-variable laser to get an action spectrum plot

of the Ulva photosynthesis and comparing it with the available action spectrum of the Ulva due to noncoherent light.

(2) Making certain correlations between the size of the chloroplast molecules (and other particles involved in the photosynthesis) and the laser irradiation frequency.

(3) Obtaining a curve of laser input power versus photosynthesis for comparison with the corresponding curve for noncoherent light.

B. EXPERIMENTS WITH NONCOHERENT LIGHT

Many experiments have been carried out for photosynthesis with various combinations of noncoherent light; we are familiar with some of them. The following suggestions are made.

(1) Since our examination of possible errors failed to account for the wide difference between our two experiments (which differed only in power range, season, and in the types of filters used), we believe that an answer might be found by performing similar experiments using filters intermediate between the two filters employed in our experiment.

(2) In general we believe that a statistical approach to the problem would be very enlightening and essential. In such an approach comparisons would be made between photosynthesis levels due to statistical combinations of frequencies and their corresponding power ratios, etc. The enhancing effect of subjecting the sample to two or more frequencies simultaneously may be profitably investigated.

(3) Finally, there is little doubt that a more elaborate approach, with well-calibrated equipment and many more measurements, would yield additional results.

V. CONCLUSIONS

A pilot experiment to determine whether coherent light exhibits biological effects different from those of noncoherent light has been performed under circumstances that sought to equalize the experimental conditions in the two cases. Nevertheless, on two separate occasions results differing by an order of magnitude (though in the same direction) were obtained. This difference cannot be explained on the basis of errors or of differences between the experimental conditions (power level, season, and optical-filter system) without postulating either nonlinearities (an assumption not justified by existing knowledge) or effects not studied in the present investigation, such as chemical reactions.

A repetition of the experiment under conditions in which additional parameters (notably frequency) can be also varied is recommended.

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APPENDIX A

Description of Clark Electrode

(Reproduced from laboratory manual for U.C. course
Physiology 100L by Prof. Lester Packer)

Description: The center (white) wire is connected to the platinum cathode; the outer (braid) wire is connected to the silver wire anode. The electrode is made from Lucite and has a nylon cap where the electrical connections are sealed. See the accompanying illustration.

Operation: The electrode may be used with any polarograph circuit where 0.60 v is available and a current-measuring device capable of reading up to about 7 ma is on hand. The electrode is designed to operate in air tensions or below but can be used to measure tensions up to pure oxygen.

1. Place electrolyte in the hole provided near the top of the Lucite tube; allow some to run out to clear out the trapped air.
2. Place the polyethylene membrane over the end and hold in place with the "o" ring. Make sure the membrane is stretched tightly over the end and conforms to the curvature of the electrode tip.
3. Fill the reservoir with electrolyte.
4. Connect anode and cathode to polarograph.
5. Check response by immersing tip in nitrogen. In pure nitrogen a zero current is found. In air one should get about 0.7 ma. Each electrode, like a pH electrode, has to be standardized before use.

For measurements in gas, the electrode may be standardized in gas. Nitrogen, air, and oxygen are useful calibrating points.

For measurements in liquids. The electrode should be standardized in the liquid being measured and provision should be made to have the liquid moving to minimize the effects of variable diffusion coefficients of the various liquids. In blood such mild stirring is important to prevent settling of red cells.

Temperature effects. The electrode decreases its reading as the temperature decreases. Thus measurements should be made at a constant temperature, although temperature calibaration (very nearly linear) curves may be constructed.

Pressure at electrode tip. The pressure of the liquid being measured for oxygen tension affects the reading since increase in liquid pressure increases the gas tensions. For this reason the electrode must be standradized under conditions of liquid pressure which are the same as those under measurement conditions or suitable corrections made.

Electrolyte. Saturated KCl solution (as used in pH electrodes) is recommended although 0.9% saline or a chloride containing buffer may be used.

Response time. The speed of response depends upon the type of membrane (e.g., cellulose acetate or polyethylene) and upon the membrane thickness. For a very fast responding electrode a 1-mil polyethylene film carefully stretched until it is transparent may be used. The tensile strength of such stretched membranes varies with the type of polyethylene used.

Sources of difficulty.

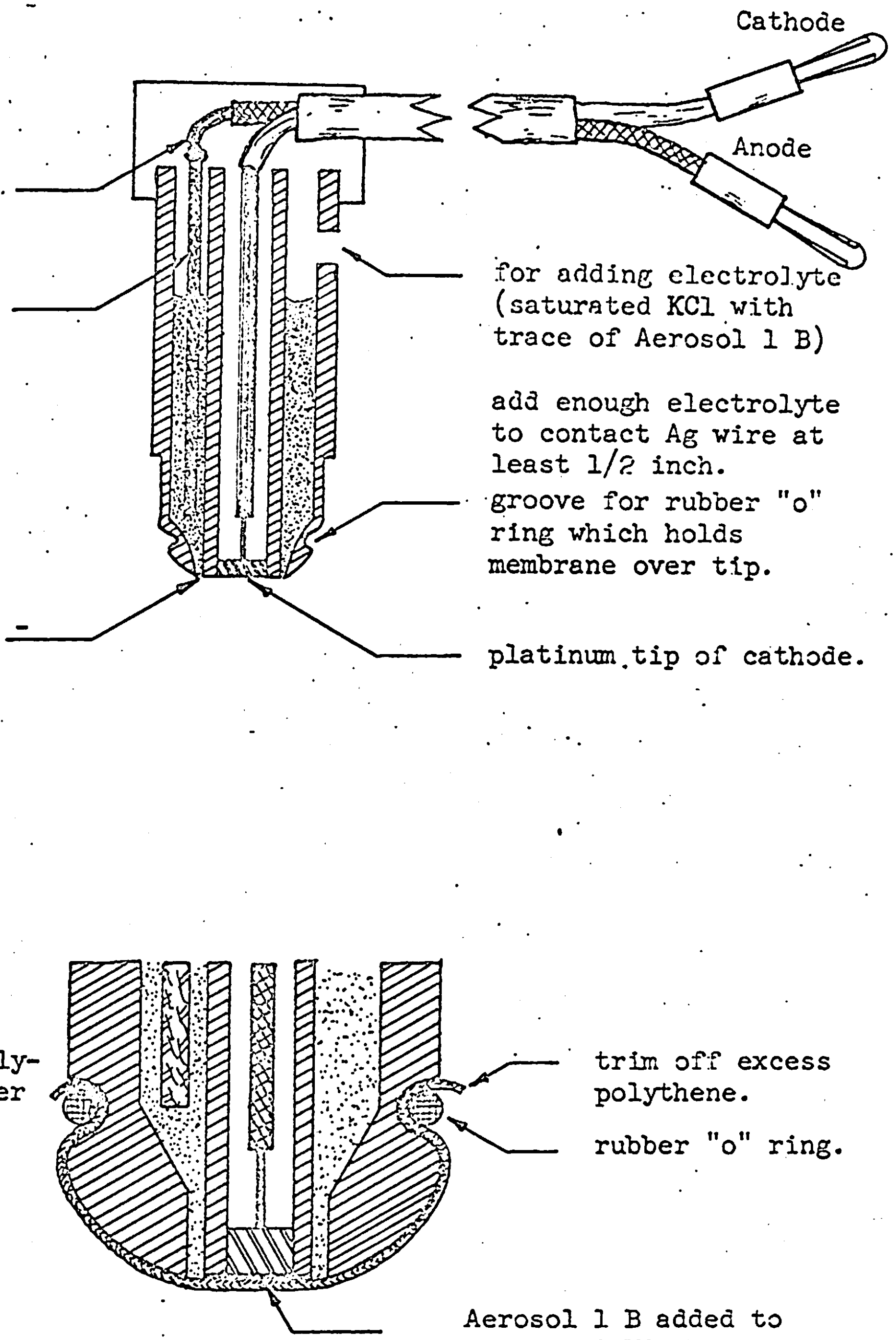
1. No current flow. Probably an air trap at electrode tip. Refill with electrolyte, replace membrane. Or tap or shake electrode (like a clinical thermometer).

2. High reading in nitrogen. Electrolyte may be contaminated (as with Fe). Use new electrolyte. Tank nitrogen may have as much as 0.7% oxygen.

3. Low reading in air. When electrode stands in air electrolyte may creep between membrane and Lucite tip. The resultant encrustations of salt crystals decreases oxygen permeability. One can cement the membrane on where prolonged readings in gas are required.

4. Very high readings--off scale. The glass cathode insulation may have cracked due to mechanical shock.

Maintenance. After use in blood, the electrode tip can usually be simply washed clean. For more thorough cleaning the membrane should be removed and the tip washed. The platinum surface may be cleaned by gently rubbing it on a finger wet with water and household scouring powder.



braid of wire soldered to anode.

AgCl-Ag reference anode

for adding electrolyte (saturated KCl with trace of Aerosol 1 B)

add enough electrolyte to contact Ag wire at least 1/2 inch.

groove for rubber "o" ring which holds membrane over tip.

small channel here - avoid air trap.

platinum tip of cathode.

gently stretch polythene membrane over tip while fitting "o" ring.

trim off excess polythene.

rubber "o" ring.

Aerosol 1 B added to saturated KCl helps wet between cathode and membrane.

Fig. 1. The Clark Electrode.
(Use electrode in upright position)

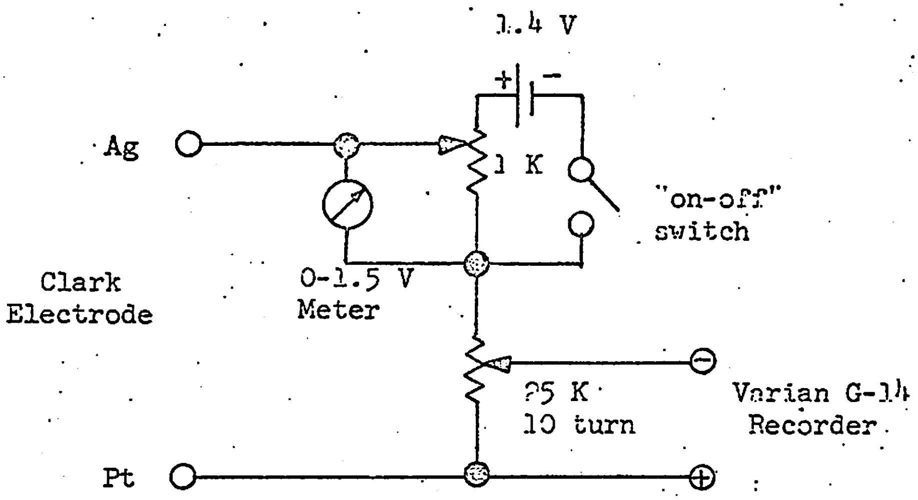
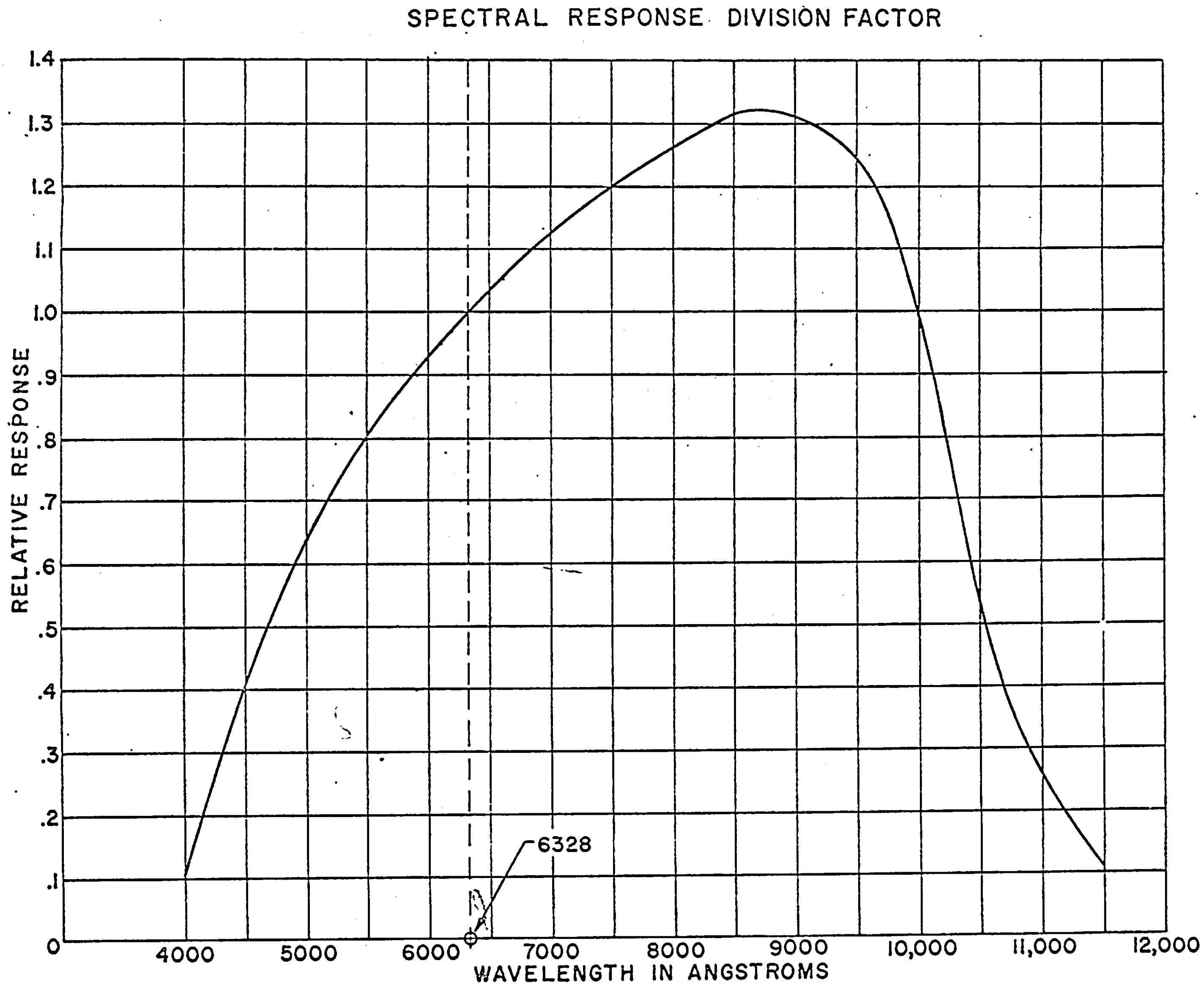


Fig. 2. Circuit diagram for oxygen electrode.

APPENDIX B

Response of Optics Technology, Inc., optical power meter Model 610



Power Requirement

Circuit and meter are powered by the detector output. No batteries or external power source is required.

Size

Head–2″ d x 4¾″. Cabinet–5⅛″ x 6⅛″ x 8¼″.

Shipping Weight

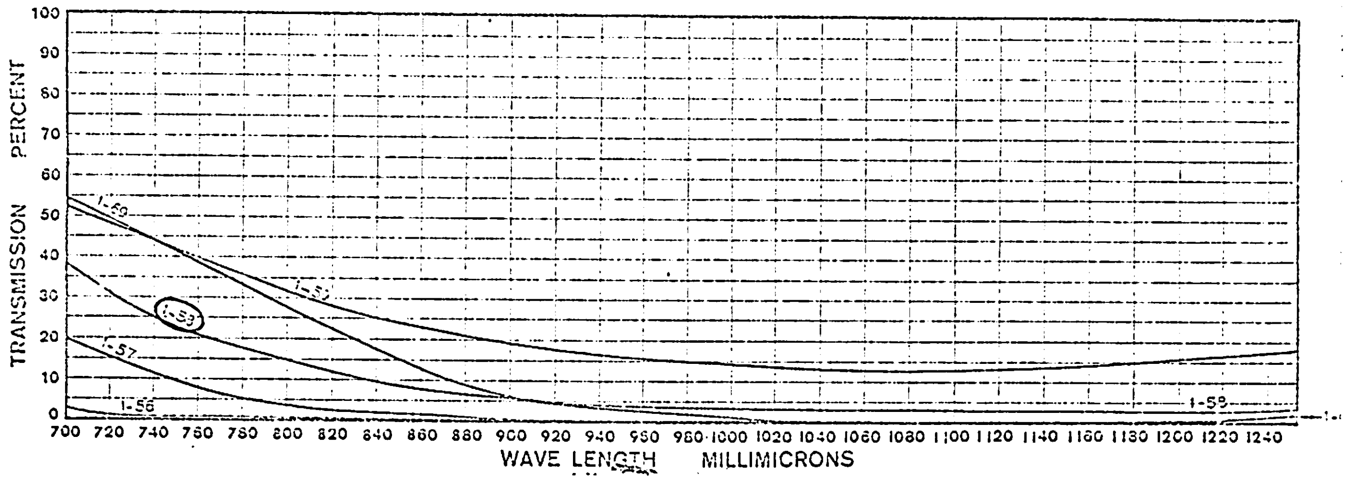
Approximately 10 pounds.

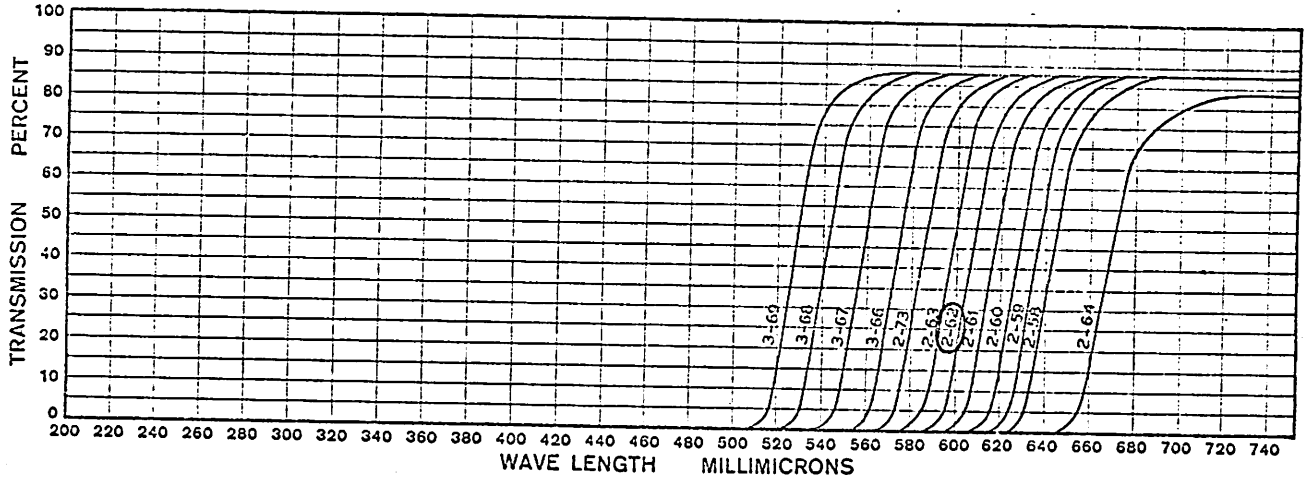
Summary Specifying Information

Optical Power Meter. Entirely self-contained unit includes six dynamic ranges to measure accurately output power of continuous lasers and other light sources at levels as low as 0.03 milliwatt. Spectral range – 4000 to 11500 Angstroms. Large 1″ diameter detector recessed to minimize effect of ambient light. Jack provided to permit direct connection of recorder or oscilloscope. Optics Technology, Inc. Model 610.

APPENDIX C

Spectral data showing spectra of Corning filters 1-58 and 2-62 (shown circled)



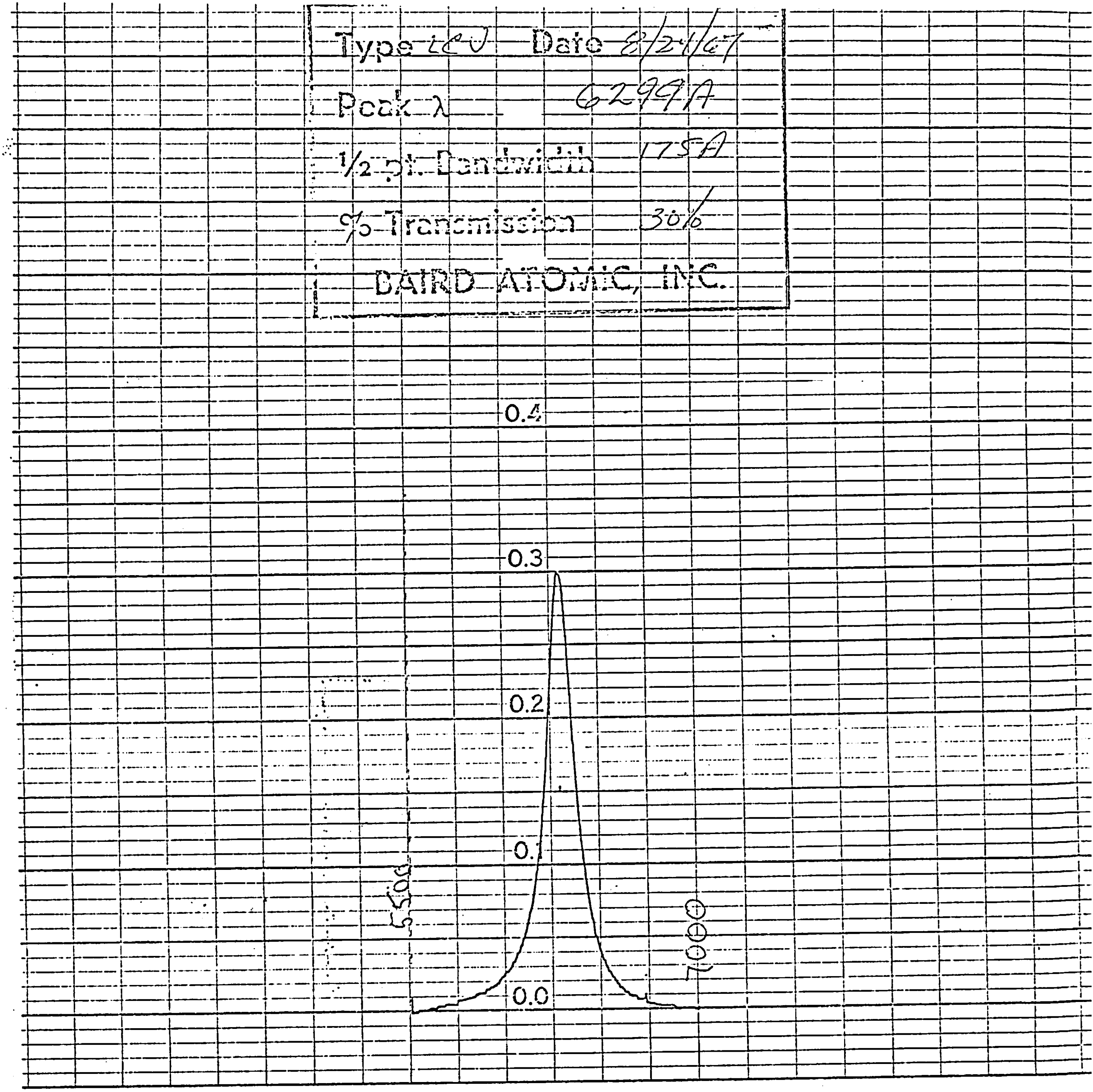


CONTROL DATA — SHARP CUT FILTERS

C.S. Number	Glass Number	WAVELENGTH (MILLIMICRONS) A	B	C	D	Expansion Coefficient	n_D
2-64	2030	648-725	750	620	—	44	1.507
2-58	2403	637-648	678	617	15	43	1.507
2-59	2404	628-637	667	608	15	43	1.507
2-60	2408	619-628	658	599	15	43	1.507
2-61	2412	610-619	649	590	15	43	1.507
2-62	2418	599-610	640	579	15	43	1.507
2-63	2424	588-599	629	568	15	43	1.507
2-73	2434	578-588	618	558	15	43	1.507
3-66	3480	567-578	608	547	15	43	1.507
3-67	3482	544-567	597	524	15	43	1.507
3-68	3484	527-544	574	507	15	43	1.507
3-69	3486	513-527	557	493	15	43	1.507
3-70	3384	491-513	558	466	20	89	1.506
3-71	3385	466-491	551	441	25	89	1.506
3-72	3387	436-466	541	411	30	89	1.506
3-73	3389	416-436	511	391	35	89	1.506
3-74	3391	400-416	491	—	35	89	1.506
3-75	3060	$T_{365} < .5\%$	$T_{405} > 40\%$			104	1.521

APPENDIX D

Spectrum of Baird Atomic filter, Type LCV



APPENDIX E

Action spectrum of Ulva (dashed line)

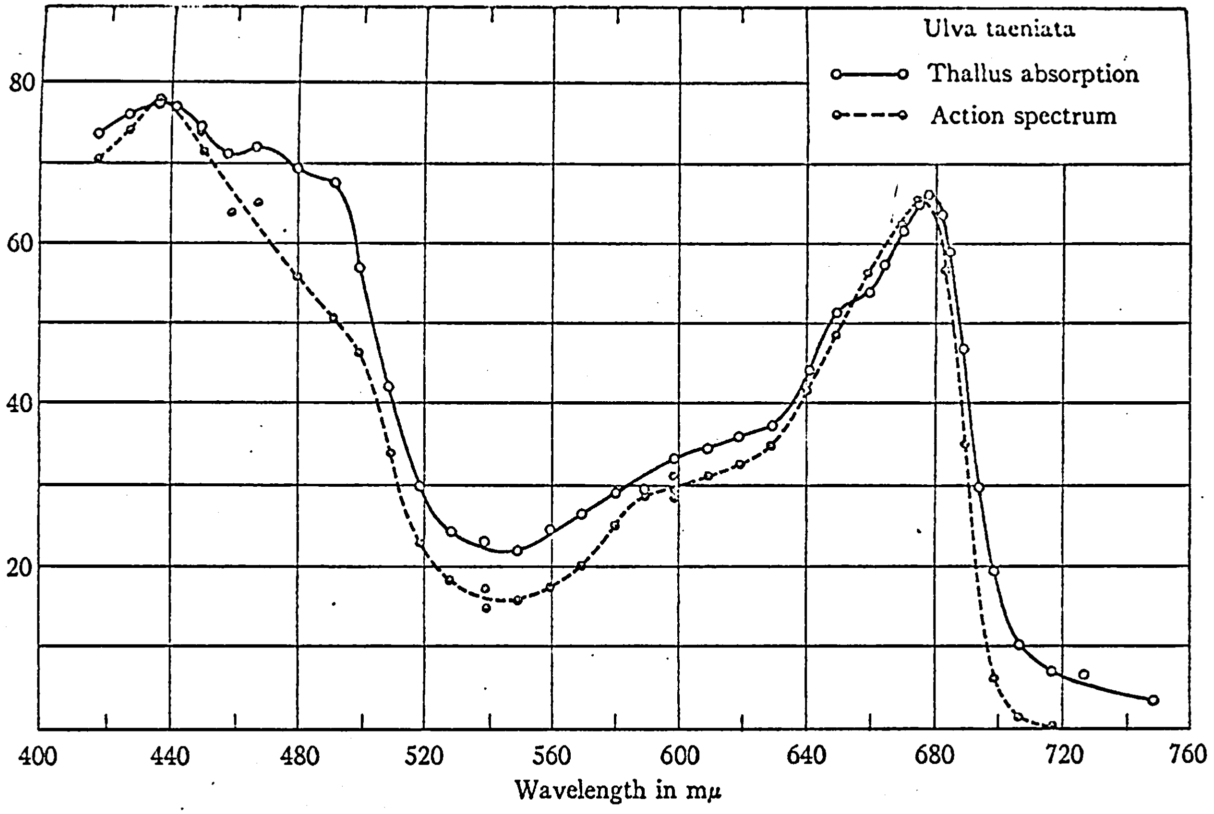


FIGURE 3.2. *Absorption spectrum and action spectrum for photosynthesis in the green alga Ulva, reproduced from a figure by F. Haxo and L. R. Blinks (Reprinted by permissions of the Rockefeller Institute Press and of the authors, from the Journal of General Physiology, March 20, 1950, volume 33, number 4, page 404). Note the relative inefficiency for photosynthesis of light absorbed by Chl a beyond 680 mμ.*

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