

of the spectra of C and especially B (which is closer to A), is serious. To combat contamination, the group tried to block out the light from A when measuring the spectra of B and C and examined ratios of spectra B/A and C/A.

Further observations in June made under conditions of excellent seeing at the MMT by Keith Hege (Steward), Angel, Weymann and Eugene Hubbard (Steward) yielded⁹ an image showing clearly the three separated images of the quasar, but also that the brightest component is not a single point object, but is elongated, indicating further gravitational splitting in the image.

Soon after the observations in June by Weymann and his collaborators, Young, Robert S. Deverill (Palomar), Gunn, Westphal and Kristian also obtained separate spectra of the A, B and C components of 1115 + 080 and confirmed that they are equal. Unfortunately, 1115 + 080, like about 95% of quasars, is radio quiet (at least down to the 1.5-millijansky flux level obtainable with the Very Large Array); so radio observations have not helped clarify what's going on.

No lens galaxy has been found optically either. Kristian told us there was no trace of such a galaxy down to 29th magnitude per (arcsec)². After doing another model calculation, the Palomar collaborators speculate that the lens is a massive spiral galaxy with both a disc and spheroidal component.

Such a lens could produce five images. One set of models predicts that the brightest image is really two close images, and the Palomar CCD data show also an elongation of the A component in the predicted direction, presumably the fourth image. And presumably a fifth image is present, too, but so faint or so close to one of the others that it can't be seen with a ground-based optical telescope. —GBL

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four bacteriochlorophyll molecules, two pheophytin and two quinone molecules attached. Although Roderick Clayton at Cornell had isolated bacterial reaction centers in the 1960's, it was not until techniques became available to incorporate them into planar synthetic lipid bilayers that the La Jolla group was able to demonstrate the direct photosynthetic transduction of light energy to electric currents by intact reaction centers.

Photoinduced potentials had been observed in 1976 by V. P. Skulachev and his colleagues at Moscow State University, with reaction centers imbedded in lipid vesicles fused to a thick film. But in this complex geometry one could not control or even know the topology of the reaction center's local environment. Reaction centers have not yet been cleanly isolated from the more highly organized green-plant cells, where they are confined in organelles called chloroplasts. But Elisabeth Gross and her colleagues at Ohio State have observed small photovoltaic potentials with chloroplast substructures imbedded in plastic filters.

A number of groups had previously studied the photogeneration of potentials in chlorophyll alone, not bound in a reaction center. But that doesn't tell one much about photosynthesis, Feher argues, because this pigment in isolation is insufficient to perform the characteristic photosynthetic processes. One can in fact get photovoltaic activity by illuminating any number of pigments.

Bacterial photosynthesis does not involve the photoinduced breakup of water and the consequent liberation of oxygen. Because bacteria must depend on other hydrogen donors, such as H₂S, organic compounds or hydrogen gas, and on more complex carbon sources than CO₂, they present a less attractive model for our emulation than do plants, which use the cheapest ingredients imaginable—water and carbon dioxide.

Photosynthesis in both plants and bacteria bears some resemblance to the operation of a semiconductor photocell. Photons induce a spatial separation of positive and negative charges, producing a potential difference that can do work. In a living photosynthetic system this light-induced potential gradient across a membrane is used to drive endothermic reactions for the chemical storage of energy, but the La Jolla group uses this voltage directly to produce external currents. They expect that the time dependence of the transient components and the steady-state levels of the photoinduced voltages and currents will serve to clarify the kinetics of the various stages of electron transfer in photosynthesis.

The photosynthetic process in bacteria begins with the absorption of a photon

Voltaic cells use photosynthesis

Photosynthesis in green plants is a quite remarkable solar-energy storage system, which one would dearly love to mimic. But after two centuries of investigation we still have only a very incomplete picture of how plants harness photons in the visible spectrum to perform the trick of knocking out of water molecules the electrons that ultimately serve to reduce carbon dioxide to energy-rich carbohydrates.

Photosynthetic bacteria make similar use of light to generate chemical energy, but by a somewhat more primitive process that may well have been an evolutionary precursor of green-plant photosynthesis. The greater simplicity of bacterial photosynthesis makes it attractive as a stepping stone to the ultimate understanding of the process in green plants, whose successful imitation could be enormously useful.

Mordechai Schönfeld, Maurice Montal and George Feher, biophysicists at the University of California, La Jolla, have recently succeeded in obtaining electric currents directly from photosynthesis,¹ by constructing a photovoltaic cell out of intact reaction centers

taken from photosynthetic bacteria and imbedded in a synthetic membrane. When illuminated, these reaction centers generate transient and steady-state voltages and currents, whose characteristics the La Jolla group hopes will elucidate the physical and biochemical processes of photosynthesis in the living bacterium.

More recently, Nigel Packham and his colleagues at the University of Pennsylvania have reported very similar results² with a photosynthetic voltaic cell illuminated by repeated laser and flash-tube pulses. The Penn group sought to clarify electron-transport mechanisms by noting differences in photoinduced currents between consecutive flashes a few milliseconds apart.

Photosynthetic reaction centers are the minimal units capable of performing the photosynthetic process in plant and bacterial cells. In a bacterium each reaction center is a highly organized chlorophyll-protein charge-transfer complex about 60 Å long, imbedded in the plasma membrane. It consists basically of three peptide chains, with

of at least 1.4 eV (865 nanometers in the near infrared) by one of the "antenna" chlorophyll molecules outside the reaction center. The photoactive group on the chlorophyll molecule consists of a magnesium atom surrounded by dihydroporphyrin ring of nitrogen and carbon atoms, whose unsaturated bonds serve a function analogous to that of the valence and conduction bands in a semiconductor—delocalizing an electron after excitation by an incident photon. This photoexcitation energy is then carried by exciton migration to a special chlorophyll dimer in one of the reaction centers, which passes an excited electron to one of the pheophytin molecules in less than 3 picosec, presumably by quantum tunneling.

The reaction center is believed to span the bacterial plasma membrane from one surface to the other. Its primary function is to drive electrons to one side of the membrane, leaving a net positive charge on the opposite side. The electron transport is accom-

plished by passing the excited electron from one acceptor molecule to the next, dropping, a fraction of an electron volt in each step of this bucket brigade. From the pheophytin, the electron passes to the first of the two quinone molecules at the far end of the reaction center. This first quinone is referred to as the "primary acceptor," the chlorophyll dimer being the "primary donor."

The second quinone then passes the electron out of the reaction center to a pool of quinone acceptors thought to be bound to the membrane surface. This transport of electrons across the membrane generates an electrochemical gradient that then serves to pump protons back through the membrane in the opposite direction. The energy inherent in the pH gradient thus generated across the width of the membrane is believed to be the driving mechanism for the enrichment of adenosine diphosphate to its triphosphate form (ATP). The 0.3 eV of chemical energy stored in this extra phosphate bond becomes the

primary biochemical currency for the later "dark" reactions that convert highly oxidized carbon compounds to energy-rich carbohydrates.

To complete the photosynthetic cycle, the primary bacteriochlorophyll donor must be reduced from its positively charged state. The necessary electron comes from a ferrous ion in the "secondary donor," a cytochrome molecule bound to the reaction center on the opposite side from the quinone acceptors.

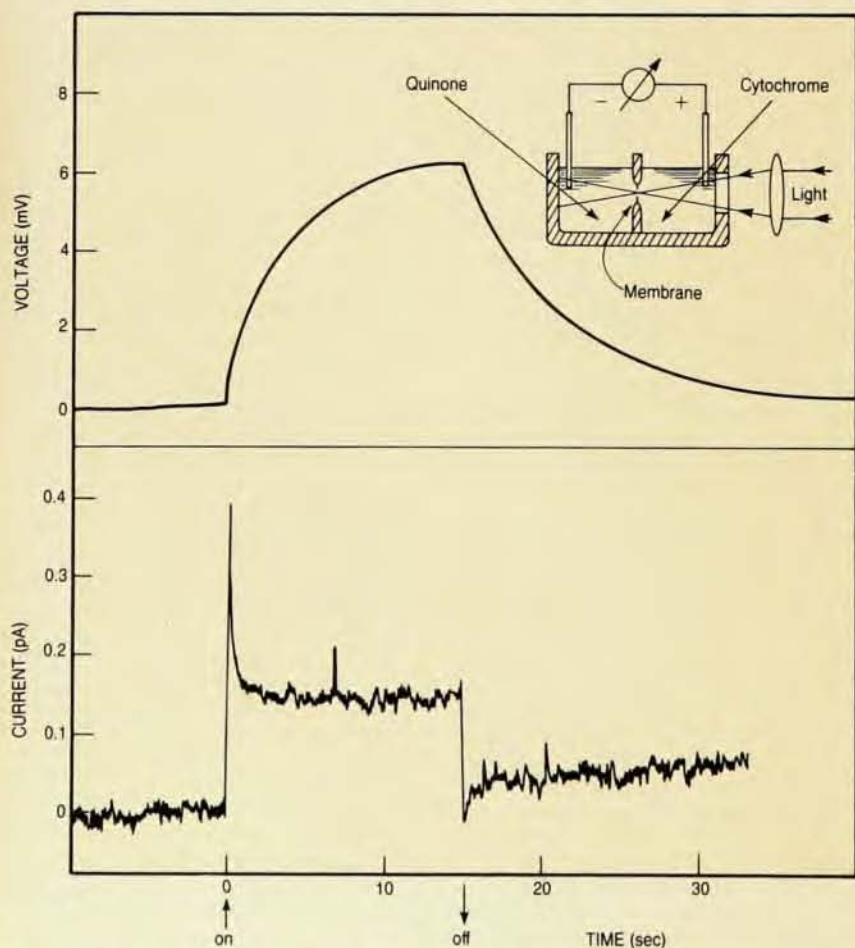
The La Jolla group has harnessed this photosynthetic charge-separation process occurring in bacterial reaction centers to drive a photovoltaic cell. They do not regard this device as a prototype of an ultimately practical scheme for the conversion of sunlight directly to electric power. Feher told us that in the foreseeable future semiconductor diodes will almost certainly do this better. But Leslie Dutton of the Penn group believes that microelectronic designers have much to learn from the extraordinary molecular organization of the reaction centers.

An attractive feature of photosynthesis is that it not only converts solar energy—it also stores it in convenient chemical form for later use. Therefore, most workers in this field are looking toward a biomimetic scheme that would use sunlight to convert water and carbon dioxide to hydrocarbons rich in chemical free energy. The purpose of the La Jolla work is to begin to understand how Nature does this trick, by monitoring the potentials in the presumably ancestral process of bacterial photosynthesis.

In a living bacterium, the photoreaction centers are imbedded in a highly convoluted plasma membrane. Because it is impractical to probe the bacterium with electrodes or to extricate and span the membrane in a photovoltaic apparatus, the La Jolla group used detergents to remove the reaction centers intact from the membrane of the photosynthetic bacterium *Rhodospseudomonas sphaeroides*. They then imbedded these reaction centers in a synthetic lipid bilayer structurally analogous to the bacterium's own plasma membrane.

This synthetic membrane is used to separate two compartments in the La Jolla photocell, containing respectively a secondary electron donor (cytochrome c) and a secondary acceptor (ubiquinone-0) in solution. Electrodes are inserted into the solutions in the two compartments to measure light-induced open-circuit potentials between them, or currents flowing when the circuit is completed.

The group found that the main features of the photovoltaic response when the bilayer was illuminated at a wavelength of 800 nm could be explained by



Photosynthetically generated voltage and current observed in the La Jolla photovoltaic cell (insert) in response to a 15-second illumination of the bacterial photosynthetic reaction centers imbedded in the synthetic membrane that separates the secondary electron-acceptor (quinone) solution from the secondary donor (cytochrome) solution. The initial current spike (observed when the 800-nm illumination of the membrane begins) and the steady-state 0.15-picoamp current indicate different photosynthetic electron-transfer processes.

a simple model of the charge separation and transport. In the absence of the secondary acceptor ubiquinone-0 in solution, a transient initial current spike was observed, but it died away quickly, leaving no steady-state current. This spike is essentially a displacement current—analogous to the polarization of a dielectric. It is attributed to the transfer of an electron from the first to the second of the two primary acceptor molecules (ubiquinone-10), made possible by the reduction of the charged chlorophyll by the secondary donor. The decay time constant of this transient is a measure of the intrinsic rates of these charge-transfer reactions.

With the secondary donor (cytochrome c) and acceptor (ubiquinone-0) in solution in their respective compartments on either side of the lipid bilayer, a steady-state current was observed to flow between the shorted electrodes for the duration of the illumination. With a density of about 10^{11} reaction centers per square centimeter of membrane, the steady current is of the order of 50 nanoamps/cm². Together with the equilibrium open-circuit voltage (50 mV), this is a measure of the reaction rate for the slower of the two secondary transfer processes—the acceptance of an electron by the ubiquinone-0.

Before they could regard these photovoltaic observations as clues to the mechanism of photosynthesis *in vivo*, the La Jolla researchers had to convince themselves that they were not laboratory artifacts. The wavelength dependence of the photovoltaic response of the La Jolla cell, peaking near 800 nm with secondary peaks on either side, is almost identical to the optical absorption spectrum of the reaction centers. The group regards this as "unequivocal" evidence that the reaction centers themselves are responsible for the observed photoelectric effect. Furthermore, the photoelectric spectrum closely resembles the wavelength dependence of electron paramagnetic resonance observed in bacterial reaction centers *in vivo*.

The La Jolla results offer direct evidence that the reaction centers span the bacterial membrane, shuttling electrons from secondary donors on one side to secondary acceptors on the other. Because the synthetic bilayer was symmetric, only half the reaction centers imbedded in the membrane had the "right" orientation—with the chlorophyll end near the cytochrome compartment. Presumably *in vivo* all the reaction centers are correctly aligned.

Having demonstrated the photosynthetic transduction of light energy into a transmission electric current, the La Jolla group plans to exploit this technique for the detailed investigation of the chain of physical and chemical

processes that make up bacterial photosynthesis. By using laser-flash techniques similar to those developed by the Penn group, they hope to determine the kinetics and reaction rates for electron transfers inside the reaction center, for example the chlorophyll's donation of an electron to the primary quinone. The steady-state currents and voltages should permit determination of the reaction rates involving the secondary donors and acceptors.

With polarized illumination one can determine the orientation of the reaction centers. The group plans to produce asymmetric lipid bilayers in order to have control over these orientations. They hope to probe the functional roles of the ferrous ion on the primary quinone and the major subunits of the reaction center, "which have this far remained elusive."

Further down the photosynthetic chain, the mechanism for producing ATP remains unclear. The group expects ultimately to use their new techniques to investigate the coupling of the photoinduced electrical potentials to this central energy-storage process.

Penn work. Nigel and Christine Packham, Paul Mueller, David Tiede and Leslie Dutton at Penn have built a photosynthetic voltaic cell very similar to the La Jolla device. Under steady illumination, their cell gave results in good agreement with the La Jolla data. But they have also exposed the membrane to repeated 20-nanosec laser flashes and 6-microsec xenon flash-tube pulses. They expect that this technique will provide additional clarification of electron-transport mechanisms in photosynthesis.

They found, for example, that the first of a sequence of flashes separated by 30 millisecc generated a much smaller transient current than did the subsequent flashes. Dutton explained to us that the weak response to the first flash is really the difference between two larger currents going in opposite directions, corresponding to the two subpopulations of randomly oriented reaction centers—with "right" and "wrong" alignments relative to the cytochrome-c added to the cell. In response to the first flash, the transfer of an electron from the cytochrome to the quinone in properly oriented reaction centers is almost canceled by an opposing current of electrons going from the chlorophyll to the quinone in the wrongly aligned centers. The 30-ms interval before the next flash is long enough for the chlorophyll situated near the cytochrome (correct alignment) to recover its lost electron from the secondary donor. But the chlorophyll in the misaligned population, having no direct access to the cytochrome, takes much longer to regain its lost electron. Thus this population is photochemically inactive during subsequent flashes, leaving a much larger unidirectional response. Results such as this tend to confirm in detail the picture of photosynthetic electron transfer that had evolved from the earlier work.

—BMS

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Nuclei may exhibit supersymmetry

Are there any interactions under which bosons and fermions behave similarly? Such a query lies at the heart of the current search for supersymmetry. A supersymmetry might be described somewhat more formally as the invariance of a Hamiltonian under a transformation operator that changes bosons into fermions and vice versa. Although the search is being most hotly pursued by particle and gravitational theorists, the first evidence for a supersymmetry in nature has surfaced in nuclear physics—as manifested in the energy spectra of some complex nuclei. This application of supersymmetry is largely phenomenological, but it has nonetheless intrigued the many theorists interested in the field.

The supersymmetry was identified¹ by Francesco Iachello (Yale University and University of Groningen) as part of his ongoing work with the interacting boson model. This nuclear model,

which is based largely on group theory (see *PHYSICS TODAY*, July 1978, page 17), has emerged in recent years as an alternative to the collective model of Aage Bohr and Ben Mottelson, both of Copenhagen. The interacting boson model depicts the nucleus as an inert core, corresponding to the last magic shell, surrounded by valence nucleons. Pairs of these nucleons act as bosons with angular momentum equal to either $L = 0$ or $L = 2$ (S and D bosons).

The interacting boson model was originally applied to nuclei with even numbers of protons and neutrons, but Iachello in his recent work extended the approach to odd-A nuclei by adding one fermion. He was able to find a group accommodating both the bosons and the fermion and to assign quantum numbers associated with this group to many of the observed low-lying energy levels (with positive parity) of the iridium-191 nucleus. (See figure.) Sub-