The leading-order Coulomb contribution for the low-energy manifold of electronic states (6, 25)is given by the two-electron permutation operator,  $P_{12}$ , which in the cases where only electronic spins are at play, reduces to the usual Heisenberg spin exchange, ~  $S_1S_2$ . For the case of a *J*-manifold, which in the absence of crystal fields is highly degenerate, it has the form of a permutation operator acting on a  $(2J + 1) \times (2J + 1)$ -dimensional space of two neighboring Yb ions. The permutation operator interchanges states  $|m_{J1}, m_{J2}\rangle$  and  $|m_{I2}, m_{I1}\rangle$  with equal weights, thus including the process  $|7/2, -7/2\rangle$  to  $|-7/2, 7/2\rangle$  where both moments simultaneously reverse, which cannot be achieved through conventional Heisenberg-Dirac spin exchange (Fig. 1, D and E). The crystal field lifts the degeneracy of the Yb moments, and although the effective interaction that emerges after the projection on the manifold of the lowest Kramers doublets  $m_J = \pm 7/2$  has the form of the antiferromagnetic S = 1/2 XXZ Hamiltonian, it retains the birthmark of its unusual origin in exchange processes that are distinct from those having the conventional Heisenberg  $J_1 J_2$  form.

The effective spin-1/2 physics emerges in Yb<sub>2</sub>Pt<sub>2</sub>Pb from the combination of high-energy (Coulomb, spin-orbit, hopping) interactions. The spin-orbit coupling virtually quenches the electronic spin degree of freedom, forcing its alignment with the large orbital moment, and in this way the effective spin-1/2 XXZ model effectively describes the quantum dynamics of the electronic orbital degree of freedom. This is directly evidenced in our experiments by the large,  $\approx 4\mu_{\rm B}$ magnetic moment carried by spinons. The orbital exchange sets the scale for these emergent quantum dynamics, which we find by comparing the measured spinon dispersion with computed spectra (Fig. 4).

Because the orbital angular momentum dominates the total Yb moment, magnetic order in Yb<sub>2</sub>Pt<sub>2</sub>Pb is synonymous with orbital order, and the configuration depicted in Fig. 1, D and E, is a natural way to understand how permutation of two neighboring electrons generates two spinons in the antiferromagnetic background. This is a process that entails charge-orbital separation, because the electron count per site is unchanged by correlated hopping, but the phases of the orbital wave function on both sites are reversed. Further-neighbor orbital exchange leads to states with four spinons (Fig. 1E). Hence, long-range hopping, either by virtue of the in-chain itinerancy of the 4f electrons or via coupling to the conduction electrons in metallic Yb<sub>2</sub>Pt<sub>2</sub>Pb, provides a natural mechanism for the spectral weight of the excitations that we observe above the twospinon but within the four-spinon continuum boundaries.

Our results provide a specific mechanism for charge-orbital separation in Yb2Pt2Pb, where the proliferation of spinons implies that electrons lose their orbital-phase identity. When united with the previous demonstrations of spin-charge and spin-orbital separation, this finding completes the triad of electron fractionalization phenomena in one dimension (26-28).

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#### SUPPLEMENTARY MATERIALS

www.sciencemag.org/content/352/6290/1206/suppl/DC1 Materials and Methods Supplementary Text Figs. S1 to S10 Tables S1 to S3 References (31-53)

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## BIOENERGY

# Water splitting-biosynthetic system with CO<sub>2</sub> reduction efficiencies exceeding photosynthesis

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Artificial photosynthetic systems can store solar energy and chemically reduce CO2. We developed a hybrid water splitting-biosynthetic system based on a biocompatible Earth-abundant inorganic catalyst system to split water into molecular hydrogen and oxygen ( $H_2$  and  $O_2$ ) at low driving voltages. When grown in contact with these catalysts, Ralstonia eutropha consumed the produced H<sub>2</sub> to synthesize biomass and fuels or chemical products from low CO<sub>2</sub> concentration in the presence of  $O_2$ . This scalable system has a  $CO_2$  reduction energy efficiency of ~50% when producing bacterial biomass and liquid fusel alcohols, scrubbing 180 grams of CO<sub>2</sub> per kilowatthour of electricity. Coupling this hybrid device to existing photovoltaic systems would yield a CO<sub>2</sub> reduction energy efficiency of ~10%, exceeding that of natural photosynthetic systems.

unlight and its renewable counterparts are abundant energy sources for a sustainable society (1, 2). Photosynthetic organisms harness solar radiation to build energy-rich organic molecules from water and CO<sub>2</sub>.

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Numerous energy conversion bottlenecks in natural systems limit the overall efficiency of photosynthesis (3). Most plants do not exceed 1%, and microalgae grown in bioreactors do not exceed 3%; however, efficiencies of 4% for plants and 5 to 7% for microalgae in bubble bioreactors may be achieved in the rapid (short-term) growth phase (3). Artificial photosynthetic solar-to-fuels cycles may occur at higher intrinsic efficiencies (4–7), but they typically terminate at hydrogen (8), with no process installed to complete the cycle via carbon fixation. This limitation may be overcome by interfacing H<sub>2</sub>-oxidizing autotrophic

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microorganisms to electrodes that generate hydrogen or reducing equivalents directly (9-14).

We recently developed a hybrid inorganicbiological system that uses the catalysts of the artificial leaf (15, 16) in combination with the bacterium Ralstonia eutropha (17) to drive an artificial photosynthetic process for carbon fixation into biomass and liquid fuels (18). In this system, water is split to oxygen by a cobalt phosphate (CoP<sub>i</sub>) catalyst and hydrogen is produced by a NiMoZn alloy at applied voltages of  $E_{appl} = 3.0$  V. Because the maximum energy efficiency is limited by the value of  $E_{appl}$  relative to the thermodynamic potential for water splitting (=  $E_{appl}/1.23$  V), a reduction in  $E_{appl}$  leads to biomass and liquid fuel efficiencies that surpass those of previous integrated bioelectrochemical systems and are commensurate with natural photosynthetic yields (18). However, reactive oxygen species (ROS) produced at the cathode were detrimental to cell growth. Because hydrogen peroxide  $(H_2O_2)$ , as well as short-lived superoxide  $(O_2^{\bullet-})$  and hydroxyl radical (HO<sup>•</sup>) species, are thermodynamically favored against  $H_2$  production at pH = 7, ROS production dominated at or below the potential to generate  $H_2$ . When  $E_{appl}$  reached a sufficient overpotential to drive water splitting, H<sub>2</sub> production to support cell growth outweighed the toxic effects of ROS (18). In addition, leaching of Ni from the NiMoZn alloy into solution inhibited microbial growth.

To develop a biocompatible catalyst system that is not toxic to the bacterium and lowers the overpotential for water splitting, we used a ROSresistant cobalt-phosphorus (Co-P) alloy cathode (Fig. 1A, pathway 1). This alloy drives the hydrogen evolution reaction (HER) while the self-healing CoP<sub>i</sub> anode (19, 20) drives the oxygen evolution reaction (OER). The electrode pair works in concert to maintain extraneous cobalt ions at low concentration and to deliver low  $E_{appl}$  that splits water to generate H<sub>2</sub> for *R. eutropha*, which supports  $CO_2$  reduction into complex organic molecules at high efficiency. The Co-P alloy, which is known to promote HER under alkaline solutions (21), exhibits high HER activity in water at neutral pH with minimal ROS production. X-ray photoelectron spectroscopy of Co-P thin films supports the elemental nature of the alloy (fig. S1), and energy-dispersive x-ray spectroscopy (fig. S2) establishes a phosphorus composition of 6 weight percent, which we have found to exhibit optimal HER activity in water at neutral pH with a faradaic efficiency of  $99 \pm 2\%$  (fig. S3). Moreover, the activity of this Co-P alloy surpasses the activity of the Earth-abundant NiMoZn and stainless steel (SS) cathodes used previously (*18*) (Fig. 1B). At constant voltage, a stable HER current is maintained for at least 16 days (Fig. 1C). Negligible H<sub>2</sub>O<sub>2</sub> is produced during HER (Fig. 1D), in contrast to that of simple metallic cathodes of Pt and SS.

The Co-P HER and  $\text{CoP}_i$  OER catalysts work in synergy to form a biocompatible water-splitting system that salvages  $\text{Co}^{2+}$  cations leached from the



**Fig. 1.** Active water-splitting catalyst pair with minimal biological toxicity. (A) Reaction diagram and scanning electron microscopy images for Co-P alloy cathode and CoP<sub>i</sub> anode. The main water-splitting reaction is shown in black; the side reactions that yield toxicants are in red. Scale bars,  $10 \,\mu$ m. (B) Current-voltage (*I-V*) characteristics of different HER catalysts ( $10 \,\text{mV/s}$ ). (C) Stability of Co-P cathode, as demonstrated by 16-day chronoamperometry. (D) Assay of H<sub>2</sub>O<sub>2</sub> accumulation for various cathodes combining with CoP<sub>i</sub> anode: yellow, Pt; blue, stainless steel (SS); red, Co-P alloy. *E*<sub>appl</sub> = 2.2 V. Error bars denote SEM; *n* = 3. (E) Cyclic voltammetry of Co<sup>2+</sup> and Ni<sup>2+</sup> in the presence of phosphate (P<sub>i</sub>). Metal concentrations are both 0.5 mM; 50 mV/s. The current for Ni<sup>2+</sup> is magnified by a factor of 50.





Fig. 2. Energy efficiencies  $\eta_{elec}$  and kinetics of the hybrid CO<sub>2</sub> reduction device. (A)  $\eta_{elec}$  values for the production of biomass and chemicals at different values of  $E_{appl}$  and various configurations (table S1). Solid bars are 5- to 6-day

averages; hatched bars are 24-hour maxima. Error bars denote SEM;  $n \ge 3$ . (**B** and **C**) Optical density at 600 nm (OD<sub>600</sub>; indicator of biomass accumulation) and amounts of electric charges that were passed, plotted versus the duration of experiments with 100% CO<sub>2</sub> (B) and air (C) in the headspace at 1 atm pressure.  $E_{appl} = 2.0 \text{ V}$ . Error bars denote SEM; n = 4 for (B) and n = 3 for (C). (**D**) A microbial growth model predicts linear correlation between electric charges and biomass accumulation, when the H<sub>2</sub> generation rate by water splitting (I/2FV) is smaller than the maximum rate of H<sub>2</sub> consumption by active biomass ( $r_{max}X_a$ ) (23) (fig. S12). Dashed line indicates Michaelis constant of hydrogenase for H<sub>2</sub>. (**E**) Real-time monitor of biomass accumulation under "day"/"night" cycle test.

# Fig. 3. Efficient synthesis of selectively produced chemicals from $CO_2$ and water (A to F) PHB [(A) at

water. (A to F) PHB [(A) and (B)], isopropanol  $(C_3)$  [(C) and (D)], and  $C_4$  and  $C_5$  alcohols [(E) and (F)] were selectively produced from the hybrid device. In (A), (C), and (E), the OD<sub>600</sub> values, concentrations of selective chemicals, and charges passed through the electrodes are plotted versus the duration of experiments. Shown in (B), (D), and (F) are averaged  $\eta_{\text{elec}}$  values for different products, measured at 24-hour intervals. Also shown are overall  $\eta_{elec}$  values combining biomass and chemical formation. The  $\eta_{elec}$ values for biomass, defined as intracellular organics excluding PHB, have been corrected to exclude the PHB interference in (B) (23) (see fig. S13 for values before correction). Error bars denote SEM; n = 3.

electrodes (Fig. 1A, pathway 2). In the cyclic voltammogram of  $Co^{2+}$  in the phosphate buffer (pH = 7) (Fig. 1E), a pre-wave to the catalytic water-splitting current corresponds to the oxidation of Co<sup>2+</sup> to Co<sup>3+</sup>, which drives deposition of the catalyst. The CoP<sub>i</sub> catalyst is also known to exhibit a deposition rate that is linearly proportional to  $Co^{2+}$  concentration (22). The self-healing property of CoP<sub>i</sub> is derived from this interplay of the potential at which OER occurs versus the potential at which the catalyst deposits (20). In concert, the Co-P and CoP<sub>i</sub> catalysts preserve extremely low concentrations of Co<sup>2+</sup> in solution through activity derived from the self-healing process. Inductively coupled plasma mass spectrometry (ICP-MS) analysis of a Co-P|CoP<sub>i</sub> catalyst system ( $E_{appl} = 2.2$  V) (23) reveals submicromolar levels of Co<sup>2+</sup> in solution after 24 hours. This concentration of  $Co^{2+}$  (0.32 ± 0.06  $\mu$ M) is well below the concentration of Co<sup>2+</sup> (half-maximal inhibitory concentration IC<sub>50</sub>  $\approx$  $25 \mu$ M) that is toxic to *R. eutropha* (fig. S4). When diffusion between the two electrodes is impeded by a porous glass frit, Co<sup>2+</sup> concentrations rise to ~50  $\mu$ M. We note that for the NiMoZn cathode, Ni<sup>2+</sup> concentrations are not regulated by self-healing, as NiP<sub>i</sub> cannot form from  $P_i$  (24), and the deposition to NiO<sub>x</sub> occurs at >1.5 V versus normal hydrogen electrode (NHE) (Fig. 1E; see fig. S5 for comparison with potentials of relevant redox processes).

Interfacing the biocompatible Co-P|CoP<sub>i</sub> watersplitting catalysts with *R. eutropha* results in a system capable of CO<sub>2</sub> fixation. The CoP<sub>i</sub> catalyst was deposited on a high–surface area carbon cloth as the electrode support (Fig. 1A and fig. S6), resulting in high currents (fig. S7) and a faradaic efficiency of 96  $\pm$  4% (fig. S8). CO<sub>2</sub> reduction pro-



ceeded under a constant voltage within a batch reactor (fig. S9), which was half-filled with a solution containing only inorganic salts (mostly phosphate) and trace metal supplements (23).

The CoP<sub>i</sub>|Co-P|R. eutropha hybrid system can store more than half its input energy as products of  $CO_2$  fixation at low  $E_{appl}$  (Fig. 2A and table S1). Entries 1, 2, 3, and 5 show that  $\eta_{elec}$  increases with decreasing  $E_{appl}$  under 100% CO<sub>2</sub> until  $E_{appl} <$ 2.0 V. Below  $E_{appl} = 2.0$  V (entry 8), a higher salt concentration (108 mM phosphate buffer) is required to facilitate mass transport and attendant current (fig. S10). However, high salt concentrations are undesirable for R. eutropha metabolism. Thus, a concentration of 36 mM phosphate and  $E_{\text{appl}} = 2.0 \text{ V}$  resulted in optimal  $\eta_{\text{elec}}$ ; the highest  $\eta_{elec}$  achieved for biomass production was 54  $\pm$  4% (entry 5, n = 4) over a duration of 6 days. Our CO<sub>2</sub> reduction efficiency from H<sub>2</sub> is comparable to the highest demonstrated by R. eutropha during H<sub>2</sub> fermentation (25). This biomass yield is equivalent to assimilating ~4.1 mol (180 g) of CO2 captured at the cost of 1 kWh of electricity. The amount of captured  $CO_2$  is 10% of the amount caught by amine-based carbon capture and storage (~2000 g at the cost of 1 kWh) (26), whose processed product cannot be used as fuel. Enlarging the batch reactor volume by a factor of 10 did not perturb the efficiency (entries 4 and 6), indicating that the system is scalable and the reactor volume does not pose immediate limits. Note that  $\eta_{\text{elec}}$ under air (400 ppm  $CO_2$ ) is 20 ± 3% (entry 7, n = 3), which is lower than for pure  $CO_2$  by a factor of only 2.7, although the partial pressure of  $CO_2$ is reduced by a factor of 2500. This indicates that  $CO_2$  is not a limiting reagent (see below). The ~20% of  $\eta_{\rm elec}$  for biomass is equivalent to assimilating ~1.5 mol of  $CO_2$  captured from about 85,200 liters of air at ambient condition with the cost of 1 kWh of electricity.

We also isolated a ROS-resistant variant of *R. eutropha* from one SS|CoP<sub>i</sub> water-splitting reactor after 11 consecutive days of operation ( $E_{\rm appl} = 2.3$  V) with a H<sub>2</sub>O<sub>2</sub> generation rate of ~0.6  $\mu$ M/min. Genome sequencing found several mutations between the strain (BC4) and the wild type (H16) (table S2). In the presence of paraquat as a ROS inducer (27), the IC<sub>50</sub> of paraquat for BC4 is almost one order of magnitude higher than that of the wild type (fig. S11). There is no obvious benefit of the BC4 strain with regard to  $\eta_{\rm elec}$  (table S1), further confirming the absence of ROS in our system (see above). Nonetheless, BC4 should find great utility for achieving high  $\eta_{\rm elec}$  in systems where ROS is problematic.

We found that biomass accumulation scales linearly with the amount of charge passed under pure  $CO_2$  (Fig. 2B) or ambient  $CO_2$  levels (Fig. 2C). The linear growth is accounted for by a model that combines governing equations for H<sub>2</sub> generation from water splitting and biomass accumulation from carbon fixation (23). The model predicts a linear correlation between biomass and charge passed after an induction period of low population density of bacteria and high H<sub>2</sub> concentration (Fig. 2D and fig. S12), which is consistent with the data shown in Fig. 2, B and C, where the induction period is too short to be observed. Gas chromatography measurements revealed a H<sub>2</sub> concentration in the reactor headspace of 0.19  $\pm$  0.04% (n = 3) in 100% CO<sub>2</sub> and 0.10  $\pm$  0.05% (*n* = 3) in air, corresponding to 1.5  $\pm$  0.3  $\mu M$  and 0.8  $\pm$  0.4  $\mu M,$ respectively, in water. These concentrations of  $H_2$  are well below the Michaelis constant of ~6  $\mu$ M for membrane-bound hydrogenases in R. eutropha (28), which suggests that  $H_2$  is facilely consumed by R. eutropha. Moreover, similar linear growth conditions for both pure and ambient CO<sub>2</sub> atmospheres provide evidence that H<sub>2</sub> oxidation rather than CO<sub>2</sub> reduction is rate-limiting for biosynthesis. Lastly, R. eutropha halted growth during "night" cycles and continued CO<sub>2</sub> reduction 12 hours later upon resumption of the water-splitting reaction (Fig. 2E), confirming the intrinsic dependence of R. eutropha on  $H_2$  generation. These data also reveal that the CoP<sub>i</sub>|Co-P|R. eutropha hybrid system is compatible with the intermittent nature of a solar energy source. Direct CO<sub>2</sub> reduction from air highlights the relatively high affinity of *R. eutropha* for  $CO_2$  at low pressures and at high O2 concentrations, in contrast to results reported for synthetic catalysts (29), individual enzymes (30, 31), and strictly anaerobic organisms such as acetogens and methanogens (11-14) (table S3).

Metabolic engineering of *R. eutropha* enables the renewable production of an array of fuels and chemical products (*17*). When *R. eutropha* confronts nutrient constraints coupled with carbon excess, the biosynthesis of poly(3-hydroxybutyrate) (PHB) is triggered in the wild-type H16 strain as an internal carbon storage pathway (*17*). As such, digestion is necessary for PHB collection (*23*). Under a constant rate of water splitting, PHB synthesis was not manifest until nitrogen became limiting ( $\sim 2$  days), as indicated by the cessation of biomass accumulation (Fig. 3A) as well as the  $\eta_{elec}$  measured every 24 hours (Fig. 3B and fig. S13). With a titer of ~700 mg/liter, the 6-day average for PHB synthesis was  $\eta_{elec} = 36 \pm 3\%$  (Fig. 2A, entry 9) with a 24-hour maximum of  $\eta_{elec} = 42 \pm 2\%$  (*n* = 3) (Fig. 3B). In engineered strains (32, 33), this PHB pathway could be modified to excrete the fusel alcohols isopropanol  $(C_3)$ , isobutanol  $(C_4)$ , and 3-methyl-1-butanol (C5), which possess energy densities of 24, 28, and 31 MJ/liter, respectively. The culture supernatant was then analyzed to quantify the secreted alcohols (23). The accumulation of these liquid fuels followed trends similar to those observed for PHB synthesis. As shown in Fig. 3, C and E, biomass production reached a plateau while isopropanol titers grew to ~600 mg/liter and  $C_4 + C_5$  alcohol titers grew to ~220 mg/liter. An engineered R. eutropha strain produced isopropanol with a 6-day average  $\eta_{elec}$  = 31  $\pm$  4% (Fig. 2A, entry 10) and a 24-hour maximum of  $\eta_{\text{elec}} = 39 \pm 2\%$  (*n* = 4) (Fig. 3D); a strain engineered to produce  $C_4 + C_5$  alcohols averaged a 6-day  $\eta_{elec}$  = 16  $\pm$  2% (Fig. 2A, entry 11) with a 24-hour maximum of  $\eta_{elec}$  = 27 ± 4% (n = 3) (Fig. 3F). The achieved titers are higher than previous reported values, and  $\eta_{elec}$  values have increased by a factor of at least 20 to 50 (10, 18). R. eutropha has demonstrated tolerance toward isopropanol (fig. S14), allowing for enriched product concentrations under extended operation.

Our combined catalyst design mitigates biotoxicity at a systems level, allowing watersplitting catalysis to be interfaced with engineered organisms to realize high CO2 reduction efficiencies that exceed natural photosynthetic systems. Because  $E_{appl}$  required for water splitting is low (1.8 to 2.0 V), high  $\eta_{elec}$  values are achieved that translate directly to high solar-to-chemical efficiencies  $(\eta_{SCE})$  when coupled to a typical solar-toelectricity device ( $\eta_{SCE} = \eta_{solar} \times \eta_{elec}$ ). For a photovoltaic device of  $\eta_{solar}$  = 18%, the Co-P|CoP<sub>i</sub>| *R. eutropha* hybrid system can achieve  $\eta_{SCE}$  = 9.7% for biomass, 7.6% for bioplastic, and 7.1% for fusel alcohols. This approach allows for the development of artificial photosynthesis with efficiencies well beyond that of natural photosynthesis, thus providing a platform for the distributed solar production of chemicals.

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#### SUPPLEMENTARY MATERIALS

www.sciencemag.org/content/352/6290/1210/suppl/DC1 Methods Tables S1 to S3

Figs. S1 to S14 References (34–49)

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#### ECOTOXICOLOGY

## **Environmentally relevant concentrations of microplastic particles influence larval fish ecology**

**Oona M. Lönnstedt\* and Peter Eklöv** 

The widespread occurrence and accumulation of plastic waste in the environment have become a growing global concern over the past decade. Although some marine organisms have been shown to ingest plastic, few studies have investigated the ecological effects of plastic waste on animals. Here we show that exposure to environmentally relevant concentrations of microplastic polystyrene particles (90 micrometers) inhibits hatching, decreases growth rates, and alters feeding preferences and innate behaviors of European perch (*Perca fluviatilis*) larvae. Furthermore, individuals exposed to microplastics do not respond to olfactory threat cues, which greatly increases predator-induced mortality rates. Our results demonstrate that microplastic particles operate both chemically and physically on larval fish performance and development.

lobal plastic production is estimated to be about 300 million metric tons (MMT) annually and is increasing by 20 MMT per year (1). As a direct consequence of the massive use of plastics in modern society, plastic waste is accumulating, especially in and around urbanized areas, where it often ends up in waterways and is ultimately transported into the ocean (2, 3). Because plastic polymers show minimal biological degradation, they remain in the environment for hundreds to thousands of

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years, where they break down into smaller pieces owing to ultraviolet radiation, physical forces, and hydrolysis (4). Hence, plastic particles continue to accumulate as small fragments (hereafter termed microplastics, and defined as <5 mm in size) throughout the world's oceans (4, 5). Plastic debris can affect marine biota both physically (e.g., by blocking the alimentary tract when ingested) (6) and chemically (e.g., by leaching toxic pollutants that are part of the plastics or that have been absorbed by the plastic) (7).

To date, passive ingestion of plastic microdebris by filter feeders is known to occur, but the ecological significance of ingestion is poorly understood (3, 4, 8). There is increasing concern that



Water splitting-biosynthetic system with CO<sub>2</sub> reduction efficiencies exceeding photosynthesis Chong Liu, Brendan C. Colón, Marika Ziesack, Pamela A. Silver and Daniel G. Nocera (June 2, 2016) *Science* **352** (6290), 1210-1213. [doi: 10.1126/science.aaf5039]

Editor's Summary

### Artificial photosynthesis steps up

Photosynthesis fixes  $CO_2$  from the air by using sunlight. Industrial mimics of photosynthesis seek to convert  $CO_2$  directly into biomass, fuels, or other useful products. Improving on a previous artificial photosynthesis design, Liu *et al.* combined the hydrogen-oxidizing bacterium *Raistonia eutropha* with a cobalt-phosphorus water-splitting catalyst. This biocompatible self-healing electrode circumvented the toxicity challenges of previous designs and allowed it to operate aerobically. When combined with solar photovoltaic cells, solar-to-chemical conversion rates should become nearly an order of magnitude more efficient than natural photosynthesis.

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