This minimized the number of completed proteins available for transport into the nucleus. Second, they were not able to detect any extranuclear or perinuclear fluorescence in purified nuclei. Third, purified nuclei were just as efficient at making new proteins as the nuclei of permeabilized cells, suggesting that proteins were not being imported from the cytoplasm. Fourth, electron microscopy revealed that nuclear translation sites (marked by biotin-lysine) were not randomly distributed throughout the nucleus but rather overlapped with transcription sites (marked by Br-UTP). Interestingly, these translation sites also overlapped with the distribution of the translation initiation factor eIF4E, the ribosomal protein L7 and, perhaps most intriguingly, the β subunit of the proteasome (which degrades proteins). Fluorescence in the nucleus increased when the proteasome was inhibited, suggesting that most newly made nuclear proteins are normally degraded. Fifth, stimulating transcription by increasing nucleotide concentrations doubled the amount of nuclear fluorescence without affecting cytoplasmic fluorescence. Together with the colocalization experiments, this finding suggests that transcription and translation in the nucleus may be coupled.

In principle, exclusion of a single vital component of the translation apparatus from the nucleus of a living cell should result in translation being restricted to the cytoplasm. How can we be sure that no such cytoplasmic translation factor leaked into the nucleus during cell permeabilization or nuclear isolation? To address this concern, the authors pretreated cells with thapsigargin—which inhibits the import of proteins into the nucleus and diffusion of proteins through nuclear pores—and then permeabilized them in the presence of the drug. This treatment effectively prevented a 40-kD fluorescein-dextran marker molecule from entering the nucleus, but did not affect nuclear translation. Although one cannot completely exclude the possibility that translation factors leaked into the nucleus, the results of this experiment are reassuring. There is no doubt that Iborra and colleagues have mounted a case of unprecedented strength in support of nuclear translation.

The Iborra *et al.* paper is sure to spur intense discussion between "believers" and "converts" on the one hand, and "nonbelievers" on the other. Doubtless, nonbelievers will demand to see nuclear translation in intact cells rather than in permeabilized cells or purified nuclei. As was the case with local translation at synapses in the central nervous system, we need more evidence to confirm that local translation products are not transported. The persuasive power of electron micrographs illustrating puromycin-sensitive nuclear ribosomes at work will win some converts. Harnessing the power of genetics and RNA interference to produce mutants that carry out either nuclear or cytoplasmic translation but not both would garner additional converts.

Few readers will fail to be fascinated by what nuclear translation can tell us about, for example, the origin of eukaryotic cells (*7*). Perhaps nuclear translation serves the same purpose as the purported restriction of translation to the cytoplasm does: namely, to prevent synthesis of faulty proteins. Nuclear translation provides the cell with an additional opportunity to assess the integrity of mRNAs before they are exported to the cytoplasm. If detected in the nucleus, "faulty" mRNAs may be subjected to intranuclear degradation or altered splicing (to avoid the production of mRNAs with premature stop codons). Such processes complement the more conventional pathway that degrades mRNAs with premature stop codons after translation by ribosomes in the cytoplasm (*8–10*). How will mRNAs that need to decode UGA stop codons for selenoprotein synthesis pass the nuclear translation test? Are proteins produced by nuclear translation functional, or are they all destined for degradation by the proteasome? What is the interplay between nuclear translation and export of mature mRNAs out of the nucleus? A recent study reports that premature translation termination codons induce the accumulation of unspliced precursor mRNAs at the site of transcription (*11*). Is this discovery a smoking gun, highlighting a consequence of linking nuclear transcription and translation? For players and spectators alike, future research on translation, whether in the nucleus or the cytoplasm, is likely to be full of suspense and surprises.

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PERSPECTIVES: SOLAR ENERGY

Solar Cells by Self-Assembly?

Jenny Nelson

In the quest for solar cells that are flexible, ultrathin, and cost-efficient, molecular solids are emerging as strong contenders. Soluble light-emitting molecular solids are already used in display applications. Solar cells made from such materials could benefit from low-tech, large-volume production techniques, greatly reducing their production cost relative to crystalline photovoltaic materials.

But molecular-solid–based devices have long suffered from low efficiencies. On p. 1119 of this issue, Schmidt-Mende *et al.* (*1*) report a photovoltaic device made from a crystalline dye and a liquid crystal that partially overcomes these problems. The very simple device converts visible photons to electrons with impressive efficiency.

The realization of an efficient organic solar cell remains a major scientific challenge. In crystalline, inorganic solar cells, the different electron affinities of the semiconductor layers create a permanent electric field, which causes the photovoltaic effect. Electron-hole pairs generated by absorbed photons are easily separated by the field.

An organic solar cell can be made to a similar design by sandwiching the organic semiconductor between two different metal contacts. However, the intermolecular forces are weaker in a molecular solid, and there is a higher degree of disorder. A photogenerated electron-hole pair (exciton) is therefore bound much more strongly and cannot normally be split by the electric fields available in the simple device. Only excitons generated within a few nanometers of the metal contact can be split, but hundreds of nanometers of material are needed to absorb most of the light.

Organic photovoltaic cells made in this way therefore achieve tiny power conversion efficiencies and low incident-photon–to–current or quantum efficiencies (QE). A good QE does not guarantee good photovoltaic energy conversion, but it is a prerequisite. Inorganic photovoltaic devices routinely achieve QEs approaching 100%; the QEs of the organic devices described so far were below 1%.

A solution was found in 1995, when several groups independently showed that QE

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could be enhanced by several orders of magnitude by blending two materials with relative preferences for positive and negative charges (*2–4*). The difference in electron affinities creates a driving force at the interface between the two materials that is strong enough to split photogenerated excitons. By blending the materials on an intimate scale (about 10 nanometers), the interface is distributed throughout the device. Hence, all photogenerated excitons are likely to find an interface and split before recombining. The separated charges must then travel through the appropriate material toward the contacts.

The QE represents the fraction that survive both charge separation and transport processes. Yu *et al.* (*2*) achieved a QE of 29% for a blend of a hole-transporting polymer with the electron acceptor C_{60}. Halls *et al.* (*3*) and Yu and Heeger (*4*) reached QEs of 6 to 8% using blends of electron-accepting and hole-accepting polymers. This greatly exceeded the QE available from either material alone.

QE enhancements have since been observed in many different material combinations. Performance has been improved through optimizing phase separation and improving device design, for instance by compositional grading (*5*). A recently reported polymer-fullerene device reached a peak QE of 50% and a power conversion efficiency of over 2% (*6*).

But QEs are still low compared with inorganic devices, even though the charge separation step is highly efficient (see the figure). The problem is that even when the mixing ratios of the blended materials are adequate for charge percolation, isolated domains in the material trap charges, causing recombination. Charges must travel through convoluted current paths, thereby increasing the probability of recombination across the large interface. Furthermore, nonlinear loss mechanisms may cause performance to deteriorate with light intensity. This constitutes a severe handicap for solar cells.

To address these problems, several groups have replaced the electron-transporting component (usually the poorer conductor) with microscopically ordered materials such as crystalline dyes, carbon nanotubes, inorganic nanocrystals, and nanorods (*7–9*). Rodlike structures are appealing because they may help channel charge directly to the contacts. The needle-like perylene dye crystals used by Schmidt-Mende *et al.* (*1*) are particularly promising because of their physical and chemical stability, high optical absorption, and the availability of soluble varieties (*9*), as well as excellent electron and exciton transport properties.

Schmidt-Mende *et al.* have gone further and also replaced the hole-transporting component with a microscopically ordered material. In doing so, they took advantage of recent developments in discotic liquid crystals. In the discotic phase, the disclike molecules self-assemble into columns aligned perpendicular to the substrate. This enables efficient intracolumnar hole transport (*10*).

The hexabenzocoronene used by Schmidt-Mende *et al.* has the highest hole mobility ever reported for a discotic liquid crystal and is unusually stable and remains discotic well below room temperature (*11*). Moreover, its low band gap permits visible light absorption and facile hole transfer to the contact. These properties make it ideal for device applications.

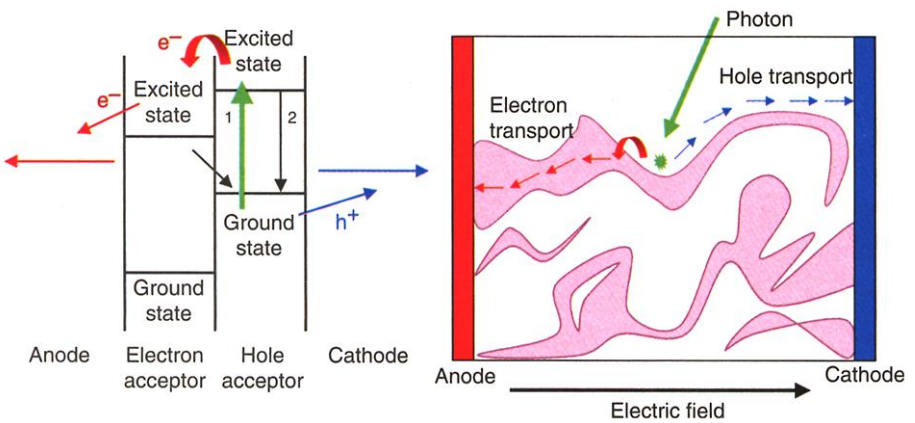
But the most remarkable result of Schmidt-Mende *et al.*'s study is the behavior of the component materials when combined. At certain blend ratios, the materials undergo vertical segregation, resulting in a predominantly perylene, electron-transporting layer above a predominantly hexabenzocoronene, hole-transporting layer [see Fig. 3B in (*1*)]. Despite the segregation, sufficient interpenetration occurs to allow good charge separation.

Compositional grading is well known to benefit both charge transport and photovoltage in solar cells but has previously been achieved only by intricate fabrication procedures; here it occurs spontaneously. Schmidt-Mende *et al.*'s device exhibits a peak QE of 34%, comparable with the best QE reported for organic photovoltaic devices. It offers, in addition, relative stability and simple fabrication.

Once QEs approaching 100% are achieved, the first obstacle to efficient organic solar cells will be overcome. Problems that remain are the relatively narrow absorption range of organic conductors, their high resistivity, and their uncertain physical and chemical stability.

Light absorption may be extended into the red by molecular modification. Some of the most exciting developments in organic photovoltaics concern the design of molecular structures in which light-absorbing units are separated from the electron- and hole-transporting components (*12–14*) and charge separation is a multistep process. Multiple-step electron transfer is the basis of photosynthesis and is already imitated in dye-sensitized solar cells (*15*). Resistivity may be lowered through development of high-mobility materials and by doping. Stability problems may be overcome through improvements in processing, encapsulation, and the use of more stable materials such as the dyes used in (*1*).

The combination of molecular design with mesoscopic self-organization could lead to simple routes to efficient and durable, organic solar cells. Schmidt-Mende *et al.* report a first step in this promising direction.



Light harvesting in an advanced organic photovoltaic device. Effective light harvesting in a blend photovoltaic device demands efficient charge separation (left) and transport (right). (Left) The energy bands of the two materials should line up to encourage charge transfer after photoexcitation. Charge separation can occur if the changes in ground state and first excited state energies have the same sign. (Right) Each material must provide a continuous path for the transport of separated charge to the contacts. Isolated domains can trap charges, whereas linear, ordered regions can act as efficient transport channels. Note that this figure is schematic; in the real system, domains are much smaller and more closely mixed.

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