Congressional Testimony

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Summary

I am here to speak to the impact of the Department of Energy Office of Science's national light sources on research and national needs primarily as it relates to energy storage and advanced materials. Synchrotron light sources are large scale facilities that are not practical for individual academic or industrial laboratories to operate. However, these facilities, funded by the DOE Office of Sciences Basic Energy Sciences program and operated by national laboratories, enable high-impact research by academic groups and industrial users, research that would not be possible otherwise. They advance our scientific understanding of matter across length scales from atomic to that which we can see with our own eyes. They provide insight to dynamics from the ultrafast timescales of the making and breaking of chemical bonds to slow mechanical fatigue processes that take more than a year. They allow us to map, in three dimensions, the composition of materials that are poised to address energy and water needs of the country and world.

My experience with synchrotron light sources began with my postdoctoral work on block copolymers for lithium batteries at Lawrence Berkeley National Laboratory. Block copolymers form structures on the scale of 100 nanometers, about 1,000 times smaller than the thickness of a human hair. These structures of block copolymers address safety concerns of lithium batteries – a major challenge in the broader distribution and utilization of energy storage technologies. However, the structure is so small that it cannot be viewed under a standard microscope, which is why we turn to synchrotron light sources. X-rays generated by light sources have short wavelengths, smaller than the wavelengths of light, that make it possible to measure nanometer scale structures such as those in block copolymers. I conducted experiments and worked with beamline scientists at four beam lines of the Advanced Light Source at Berkeley Lab and one beam line at the Stanford Synchrotron Radiation Lightsource.

As an independent investigator, my group still works with scientists at Berkeley Lab, but we now also use several beam lines at the Advanced Photon Source at Argonne National Laboratory. This makes it possible to perform time-resolved experiments (similar to movies) of the dynamics of block copolymers and polymer nanocomposites (mixtures of polymers and small particles) that are relevant for lithium batteries. With proposed upgrades it will be possible to look at essential dynamics occurring over smaller length scales that are simply inaccessible now.

We are now interested not only in materials for lithium batteries, but also in membranes for water purification. In both of these areas, identified as grand challenges by the National Academy of Engineers, heterogeneous polymers are promising materials – understanding dynamics in them is crucial to enabling technological solutions to these challenges. It is only with these exceptionally bright light sources (one billion times that of the sun and slated to increase by a factor of at least 100 with proposed upgrades) that rapid experiments on extremely small length scales are possible to further our understanding of advanced materials, such as block copolymers, for energy storage and water purification.

My work has touched on only a small fraction of the types of experiments that can be conducted at light sources. The capabilities are crucial for a vast range of technologies of national importance. These include characterization of both hard and soft materials for energy generation and storage, investigation of electronic and photonic materials for sensing and computing, and a wide-range of biological applications. It is imperative that these facilities receive robust funding for operations, and also receive the funding necessary for upgrades that will allow them to address the critical science challenges that our nation must solve going forward.

Statement

Chairman Weber, Ranking Member Grayson, and Members of the Subcommittee, thank you for the opportunity to testify in today's hearing on Innovation in Solar Fuels, Electricity Storage, and Advanced Materials. I am here to speak to the impact of the Department of Energy's national light sources on research and national needs primarily as it relates to energy storage and advanced materials. I thank the committee for its long-standing and robust support of our national light sources. I understand that there are upgrades proposed for some of these light sources. Although I strongly support upgrading the nation's portfolio of light sources, based on my personal area of expertise, I will not speak in detail about the upgrade proposals. Rather, I will emphasize the importance of these national light sources and explain how the upgrades would advance U.S. research capabilities.

My interest in alternative energy began in the mid 1990's, when I was first exposed to hydrogen fuel cells by my undergraduate Chemical Engineering advisor, Professor Javad Tavakoli, at Lafayette College. Eventually I was led to graduate school at Drexel University with Professor Joe Elabd, where I became an expert in polymers and in time-resolved experiments. Based primarily on his reputation, I acquired a postdoctoral fellowship at Lawrence Berkeley National Laboratory with Professor Nitash Balsara. In order to enable safer, longer lasting batteries, we demonstrated a completely solid battery using block copolymer electrolytes. I am now an assistant professor in Chemical and Biomedical Engineering at Florida State University, where my group uses synchrotron light sources to study structure and dynamics in heterogeneous polymer materials for lithium batteries and water purification.

A battery contains two electrodes separated by an electrolyte. Electrolytes are essential for battery operation because they conduct ions (charged molecules) between the electrodes when a battery is charged or discharged. Commercial lithium ion batteries contain liquid electrolyte that can explode and burn if abused. Although there are engineering controls for safety, commercial lithium ion batteries are not inherently safe. Examples of this abound, a high-profile and recent one being the overheating of lithium ion batteries in Boeing Dreamliners. In addition, liquid electrolyte is not compatible with many of the advanced battery electrodes that have been developed in recent years.

Polymers, on the other hand, are large molecules. Examples include plastic, rubber, plexiglass, wood, and DNA. It is possible to connect dissimilar polymers together to form a block copolymer. These are amazing materials. The two polymers try to separate like oil and water, but the connection prevents complete separation. As a result, intricate structures are formed on molecular length scales. The nanotechnology that has revolutionized our technological landscape since the turn of the century relies primarily on properties of materials that emerge from interfaces, i.e. interactions between different materials. Block copolymers are a prime example of a nanomaterial because they can combine the ion conduction property of one polymer with the strength of another polymer, which is not possible with simple mixing.

Block copolymer electrolytes hold promise for developing safer batteries that can last ten times longer between charges than existing batteries.[1] They are amenable to flexible laminar cell construction, which holds the potential for significant cost savings.[2] The ability to combine disparate properties into a single material makes block copolymers of interest for water purification as well, where a strong material is needed that can conduct water but not contaminants. For successful operation of block copolymers in these technologies the structure and the dynamics of the material is important. The structures in these materials are extremely small, about 1,000 times smaller than a human hair. It is quite challenging to image on this scale with a microscope, especially a soft material such as a polymer. Therefore, we turn to synchrotron x-rays, found at our nation's light sources, which can be used in a variety of ways to determine the structure, dynamics, and composition of a material.

Synchrotron Light Sources

A schematic of a synchrotron light source is shown in Figure 1. It is overlaid on a baseball diamond for scale. This is roughly the size of the Advance Light Source in Berkeley operated by Lawrence Berkeley National Laboratory, which specializes in soft (low energy) x-rays that make it possible to map the composition of elements in a material on an extremely small length scale. The Advanced Photon Source in Chicago, operated by Argonne National Laboratory, is nearly six times larger and produces hard (high energy) x-rays that enable time-resolved experiments again on extremely small length scales. The National Synchrotron Light Source II at Brookhaven National Laboratory is a medium-energy light source. There are also synchrotron sources operated by SLAC National Accelerator Laboratory. These facilities are all supported by the Department of Energy, although an additional U.S. synchrotron facility is operated by Cornell University under National Science Foundation funding. Each of these light sources has unique expertise and capabilities that provide access to complimentary experiments and imaging characteristics.

A synchrotron generates x-rays by accelerating electrons to near the speed of light and then bending them with magnets around the ring depicted in Figure 1. As the electrons pass through the magnets they emit radiation (light) over a wide spectral range including infrared (energy less than visible), but primarily as x-rays. Many experiment stations are situated around the ring achieving a wide variety of experiment types available at each facility. Access to these facilities is free and competitively awarded. The demand for these experiments requires that they operate around the clock. In order to maintain the research innovation that drives the success of U.S. technology in the competitive world economy, it is important to implement technological upgrades to the synchrotron light sources themselves. Doing so will allow U.S. researchers like myself to continue to perform cutting-edge research domestically.

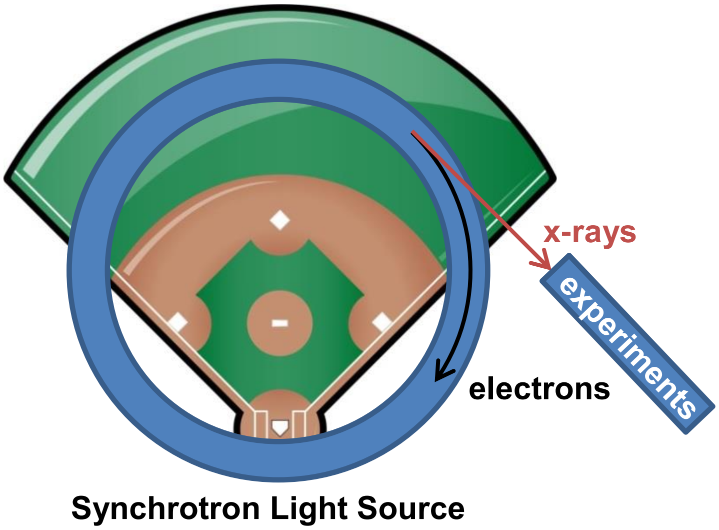

Figure 1. Schematic of a synchrotron light source overlaid on a baseball diamond for scale.

The wide range of energies achieved by the aforementioned Department of Energy light source user facilities make possible an immense range of unique experiments. They can be categorized into three main types: scattering, microscopy, and spectroscopy. Scattering can probe structure and dynamics of complex materials across an immense range of length and time scales. Microscopy provides a three dimensional look inside materials. Spectroscopy determines the make-up of a material. The most powerful experiments are combinations of these three experiment types. These experiments are applied at our nation's light sources by thousands of researchers each year in the fields of materials, chemical, and life sciences, as well as physics and geological sciences. This research also generates thousands of research publications each year contributing significantly to the nation's technology and innovation-based economy. Most exciting to me are the numerous scientific discoveries that would not be possible without these facilities. For example, a new form of matter has been discovered called topological insulators. The most-prescribed drug for HIV, the fuel injectors at the heart of modern gas engines, the battery for the Chevy Volt electric car – all of these crucial discoveries, plus thousands more, were made possible by these user facilities.

With upgrades to these facilities other barriers will come down, making it possible to see structural changes at the atomic level that happen before a steel girder starts to crack, before a healthy brain succumbs to Alzheimer's, and before an electric car's battery begins to fail. Researchers will be able to observe individual atoms moving and reacting – in real time, deep inside real samples, organisms and systems. Researchers will be able to observe every aspect of battery function and failure at every length scale, gleaning atomic-level information to speed development of the safe, reliable, powerful and affordable next-generation batteries we need to transform energy storage for transportation and the power grid.

Longer Lasting Batteries

The interface between electrolyte and electrode is a crucial component of a battery that for the most part dictates the lifetime of a battery. In order to study the products that form at these interfaces my laboratory has developed new techniques for coating electrode surfaces with nanoparticles. These nanoparticles can be finely tuned to control both optical and electrical properties of the interface. These properties are controlled by the spacing and size of the nanoparticles. As shown in Figure 2, we have used x-ray scattering to measure both particle size and particle spacing. X-ray scattering provides quantitative measurement of a large sample but can detect extremely small differences in spacing, which are important for controlling properties. These nanoparticle coatings will be used to examine the products that form on the surface of advanced electrodes in contact with liquid or polymer electrolyte. Our project has the potential impact of increasing battery energy density by 50 to 100%. In addition, we will gain better understanding of chemical changes occurring in operating batteries. Without x-ray scattering we would enter this research rather blindly without good understanding of the structure of our materials.

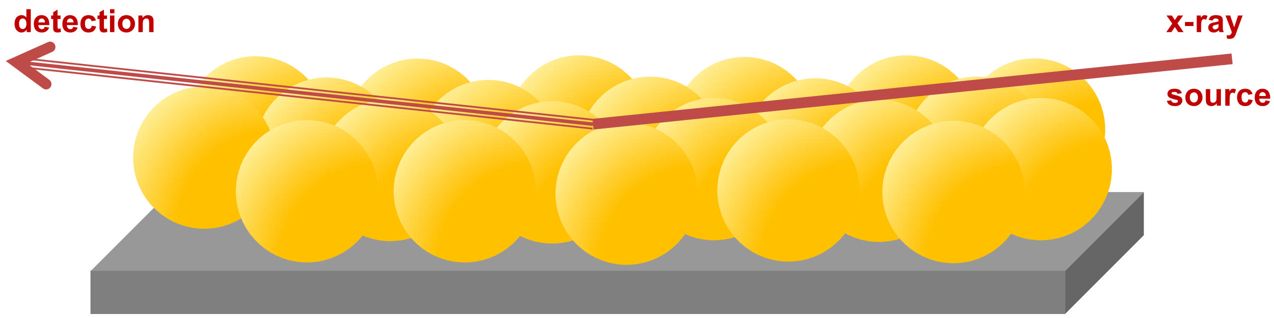

Figure 2. Schematic of x-ray measurement of nanoparticle size and spacing.

Advanced Materials

The fuel economy of conventional vehicles has increased by 5% since 2000[3-4] due, in part, to transition from steel to aluminum bodies. There is now interest in transitioning to much lighter nanocomposites that can further improve fuel efficiency not only in automobiles but also in aircraft.[5] Designing stronger, lighter polymer composites requires understanding the adhesive properties of the polymer within the material, which depend on polymer dynamics. Even greater improvements in transportation efficiency can be achieved by replacing conventional engines with battery-powered electric motors.[6] Realizing this requires improving both battery lifetime and rate capability. Lifetime is limited by adhesion between polymer electrolyte and the battery electrodes. Rate capability is limited by the ion conductivity of the polymer electrolyte, which like adhesion is coupled to polymer dynamics. Therefore, we are investigating dynamics in block copolymer electrolytes and polymer nanocomposites using time-resolved x-ray scattering techniques.

Energy Efficient Water Purification and Desalination

The National Academy of Engineering has identified access to clean water as a grand challenge in the 21st century[7]. By the year 2040, 6 billion of the projected 9 billion people on the planet will live in water stressed regions[8]. In order to supply potable water in these regions, water either needs to be reclaimed and purified or desalinated. Polymer electrolyte membranes are integral to energy efficient water desalination and water reclamation. The cost and energy requirements of these processes depend on the rate at which water is transported through the membrane and the efficiency with which salt and contaminants are rejected[9-10]. A common problem in water purification is membrane fouling[11-12], in which microbes adhere to the membrane surface blocking water molecules from permeating the membrane and increasing both cost and energy consumption. Heterogeneous polymer electrolyte membranes can potentially address these problems. The structure of these materials is a function of water content and salt concentration. We are investigating the evolution of this structure using x-ray scattering and the resulting effect of structure on water transport and fouling. By developing membranes with selectivity for water over salt and contaminants that are resistant to fouling, a significant impact can be made on energy efficient generation of fresh water.

Human Health

Although not a topic of my research, human health is a significant national concern that is greatly impacted by synchrotron light sources. Alzheimer’s disease is now our nation’s 6th leading cause of death. High brightness and tight focus enabled by synchrotron upgrades will make it possible to observe the initial processes that cause brain proteins to start to deform – processes that occur too quickly for current technologies to capture, and that must be understood before we can learn to interrupt (or even prevent) Alzheimer’s and related brain diseases.

I had the opportunity to tour a second generation light source (the Bevatron) before it was demolished. Toward the end of the tour, the tour guide pointed out an area where there had been curtains and they brought in patients for cancer treatment. This work was initiated by Ernest Lawrence, Nobel Prize winner and founder of Lawrence Berkeley National Laboratory, and his brother, who was a physician, at an even earlier facility. The scene, something like a large warehouse with a massive concrete ring in the center (the synchrotron) and an examination area for patients in gowns struck me. This image speaks not only of the importance of the work that goes on at these facilities (the technique in question is used today to treat cancer that is not responsive to other treatments), but also of the scale (these are facilities that require federal funding and are appropriately housed at national laboratories). It is imperative that these facilities receive robust funding for operations, and also receive the funding necessary for upgrades that will allow them to address the critical science challenges that our nation must solve going forward.

Biography

My given name is Daniel Thomas Hallinan Jr. I am originally from Pennsylvania, where I attended Catholic schools through high school. In 2001, I received a Bachelor of Science degree in Chemical Engineering and a Bachelor of Arts in Philosophy from Lafayette College. After a hiatus from academics, I returned to Drexel University where I received a PhD in Chemical Engineering in 2009, studying the transport of ions and water in polymer electrolyte membranes for hydrogen fuel cells under Dr. Yossef A. Elabd. Having discovered the reward of teaching, I continued on the academic track with a postdoctoral fellowship at Lawrence Berkeley National Laboratory (LBL). There I studied block copolymer electrolytes for lithium batteries in Prof. Nitash P. Balsara's laboratory, conducting a variety of hard and soft x-ray scattering, tomography (3D imaging), as well as some x-ray spectroscopy at the Advanced Light Source of LBL. Now as an independent investigator at Florida State University (FSU), my students and I use several beamlines at the Advanced Photon Source (APS) of Argonne National Laboratory. FSU recognizes the importance of user facility research and supports our travel to the APS. With the hard x-rays of APS we are able to examine block copolymer and nanoparticle dynamics. Experimental measurement of local dynamics in heterogeneous polymer materials is unprecedented. These measurements promise to unravel intriguing observations of kinetic properties in nanostructured polymer materials that are significantly different from those in the bulk materials. We are eager to investigate faster processes on shorter length scales that will be made possible by the proposed upgrades.

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