Towards electrochemistry of single molecules: Nanoscale studies of redox processes

Contrary to common opinions, electrode processes studied and designed by electrochemists constitute an essential part of our lives. They occur, for example, on electrodes that one can find in batteries of laptops and cell phones. Recently, batteries are also used to power vehicles. Each of us wants these devices to be lightweight, durable, fast charging and able to store a large amount of energy. Progress in all branches of electrochemistry over the centuries to further development requires understanding these processes at the level of the individual molecules of which all the matter is made. Electrochemistry includes not only batteries but also sensors of harmful substances, devices for deposition of layers protecting against corrosion, and large electrolyzers for industrial production of materials that cannot or are not profitable to obtain with other methods. For example, most electrical wiring is made of electrochemically refined copper. Even processes in living organisms are studied using electrochemical methods. An essential process in our cells is the inactivation of reactive oxygen species that destroy cells and accelerate aging. Gray hairs, one of the visible effects of aging, results from the reduction of enzymes in the body responsible for neutralizing these deadly forms of the life-giving element. One of these forms is hydrogen peroxide. Until recently, it was sold in pharmacies for disinfecting wounds. It has now been replaced by alcohol-based solutions that disinfect just as effectively but heal faster. Anyone who has had the opportunity to see a wound sprayed with hydrogen peroxide solution knows that foam is then released. Each foam contains tiny gas bubbles. In this case, this gas is the oxygen we need to breathe. It is released due to the decomposition of hydrogen peroxide into water and oxygen. Such instability and decomposition of hydrogen peroxide are caused by catalase - an enzyme that dramatically accelerates this decomposition reaction. One molecule of such an enzyme (protein) can break down over a million hydrogen peroxide molecules in a second. It is often said that this reaction is then diffusion-controlled, i.e., the rate at which H_2O_2 molecules reach the enzyme molecule and discharge the resulting oxygen.

Scientists from the Institute of Physical Chemistry of the Polish Academy of Sciences in Warsaw, Poland, have developed small electrodes that can be used to study the process of decomposition of hydrogen peroxide. These electrodes are a thousand times smaller than the diameter of human hair. According to preliminary calculations, recording the signal from single catalase molecules is possible with such a tiny electrode. This is, however, difficult due to noise caused by, among others, electromagnetic pollution that is ubiquitous today. The way to eliminate this noise would be to convert the electrical signal into a light signal. The latter is easy to measure at the level of single photons (the smallest values of energy transmitted by light). Thanks to such signal conversion, it will be possible to study electrochemical processes at the level of single events. This will make it easier for scientists to fully understand these processes so that our batteries can be designed to be even smaller, more durable, lighter, recharge faster and deliver a large amount of energy in a short time if needed.