

certain what electrons could do by themselves. He prepared a contaminant-free Si(100) surface, examined it under a scanning tunneling electron microscope in ultrahigh vacuum (5×10^{-11} torr), exposed it to the beam from a LEED electron gun, and then reexamined it under the STM.

Clear and extensive evidence of surface modification prompted Nakayama and Weaver to study the effect systematically for a range of surfaces, exposures, doping levels and electron energies. The figure on this page exemplifies the data they collected.

In general, it appears that electron irradiation promotes the proliferation of some of the same sorts of defect that are present in small concentrations on pristine surfaces and larger concentrations on etched surfaces. For the Si(100) surface, these defects are principally dimer vacancies, which involve pairs of missing surface atoms, and so-called C-type defects, whose nature remains to be definitively established. Under exposure to 2000-eV electrons, the density of dimer vacancies increased almost sevenfold.

Nakayama also exposed Si(111) and GaAs(110) surfaces to electrons. The density of defects on those surfaces increased, too.

How exactly do the incoming electrons knock out surface atoms? Weaver proposes that inelastic cascade scattering is responsible. As they bounce off atoms, electrons are captured at antibonding surface resonances (surface potential wells). To accommodate the captured electrons, the atoms reconfigure by moving further apart, which makes it possible for atoms to desorb, move onto a terrace or do both.

According to Ted Madey of Rutgers University, experimentalists have known (or should have known) for many years that energetic electron beams induce electronic excitations that can damage monolayers of gases on surfaces and the surfaces of many compound materials (like oxides). "What's new here," points out Madey, "is the recognition that even elemental semiconductor surfaces can be damaged, and with relatively high probability."

Reassuringly, Klaus Heinz (University of Erlangen-Nürnberg) doesn't think the consequences for LEED are disastrous. Heinz explains that LEED is a "forgiving method," in that only well-ordered patches on the surface contribute to the diffraction spots. Defects end up in the diffuse background, which is routinely subtracted anyway. To check for electron damage, he recommends repeating the intensity measurement: "If the data of the repeated measurement agree with the

first data, things are okay."

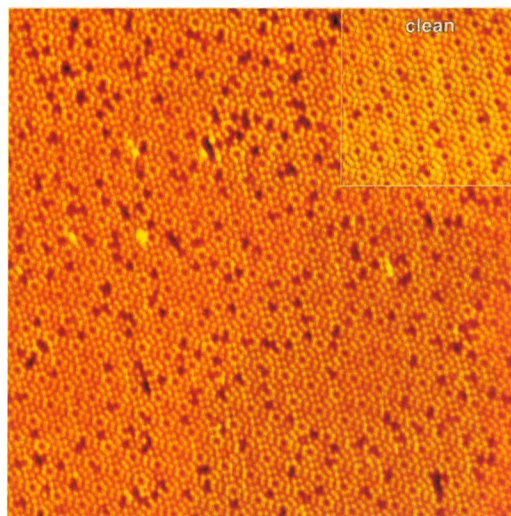
Evil, be thou my good

When Weaver first saw the postbombardment STM images, his reaction was, "Wow, that's neat!" His delight arose from the possibility that electrons could be used to deliberately modify semiconductor surfaces.

Weaver envisions that a kind of electron-photon tag team could pattern surfaces without using chemicals, which are often toxic and always have to be removed and disposed of when etching is complete. The electrons, thanks to their strong elastic and inelastic scattering, would broadly sample the energy landscape of the surface and crack open defects. Entering the ring next, a tuned laser could widen the defects by resonating with a desorption state.

The prospect is not fanciful. Last year, Hans-Joachim Ernst, Fabrice Charra and Ludovic Douillard of CEA Saclay demonstrated that lasers can induce atomic-scale restructuring of single-crystal copper surfaces.⁴ And Weaver's group has already demonstrated the tag-team approach for GaAs(100).

CHARLES DAY



BEFORE AND AFTER. The inset shows a scanning tunneling microscope image of a clean silicon(111) surface. The main panel shows the same surface after it was exposed to $2 \times 10^{16} \text{ mm}^{-2}$ electrons at 90 eV. The concentration of adatom vacancies increased by 50%. (Figure courtesy of John Weaver.)

References

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Is the Island of Stability in Sight?

Researchers from the Joint Institute for Nuclear Research in Dubna, Russia, and from Lawrence Livermore National Laboratory, claimed in January that they had produced element 114. The news raised hopes in many quarters that this sighting, like the appearance of a shore bird after a long sea voyage, might be a harbinger of the long-sought island of stability, a region populated by superheavy elements whose halflives might range up to hundreds or thousands of years. The reported atomic number of 114 is in the vicinity of the magic numbers associated with increased stability, according to most theoretical calculations. The alleged lifetime, while only 30 seconds, is still orders of magnitude greater than the halflives of isotopes produced to date in the atomic number range 109–112.

Reactions to the announcement are tempered by the need to confirm the result. The Dubna–Livermore group has seen only a single atom. Moreover, the researchers produced it in an

▶ Will a single nucleus turn out to be just what its discoverers think it is—a relatively long-lived isotope of element 114 lying in or near a region of very stable heavy nuclei?

unexplored region of the chart of nuclei, so one cannot link the daughters and granddaughters of its decay chain to any known isotopes.

An attempt to confirm the result is already in the offing. A team at Lawrence Berkeley National Laboratory has been planning all along to do the same experiment and will try for element 114 this summer. One of the long-time team members, Albert Ghiorso, was so enthusiastic about the prospect of reaching the island of stability that he confessed, "I'd trade five of the elements Berkeley has produced for this one from the Russians." Unfortunately, Glenn Seaborg, long-time leader of the Berkeley team, died on 25 February after suffering a stroke last summer.

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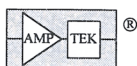


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Magic numbers

The prediction of an island of long-living superheavy nuclei grew out of the shell model of nuclei, which first explained the high binding energy and abundance of nuclei with certain numbers of neutrons and protons. Those so-called magic numbers correspond to fully occupied neutron or proton energy levels. Well beyond the naturally occurring elements, theorists expect to see a cluster of very long lived isotopes, centered near a doubly magic nucleus. (See PHYSICS TODAY, February 1999, page 21).

Just what are the magic numbers for the superheavy elements? Theorists seem to agree that a neutron number of 184 may be magic, but differ on where the magic atomic number Z might be; some calculations put it at $Z = 114$; others, in the range from 120 to 126. The isotope claimed by the Dubna-Livermore group, $^{289}114$, is close to this range.

Hot fusion reaction

The Dubna-Livermore collaboration, led by Yuri Oganessian, conducted its experiment at Dubna's U-400 cyclotron. The experimenters used the conventional method of hot fusion, in which a high-energy projectile is hurled at a heavy-element target, forming a compound nucleus in a highly excited state. In the recent experiment, the researchers directed a beam of calcium-48 atoms at a target of plutonium-244 to produce the compound nucleus, $^{292}114$. Most of the compound nuclei decay by fission, but a few may cool down by shedding only a few neutrons before succumbing to a chain of alpha decays. Most likely, say the experimenters, the compound nucleus in the Dubna-Livermore experiment threw off three neutrons, becoming $^{289}114$, the nucleus that has created the recent stir. It was seen to decay by a chain of three alpha decays followed by a spontaneous fission event.

To detect the reaction products, Oganessian and his team used a gas-filled, on-line mass separator. In this apparatus, reaction products recoiling from the plutonium target quickly achieve a uniform charge state through charge-exchange reactions with a low-pressure volume of hydrogen gas. A magnetic field separated the compound-nucleus products from the products of unwanted nuclear transfer reactions and from unreacted beam ions. The remaining nuclei passed through two time-of-flight sensors (to determine the velocities) and landed on a position-sensitive detector. The detector recorded the times and energies of radioactive decay products. Ken Moody,

one of the Livermore collaborators, told us that they collected data for 40 days, keeping track of the decays seen at every position on the detector where a nucleus had landed.

Because this region of nuclei with neutron and proton numbers in the range of the purported new isotope is so far unexplored, the decay times cannot be associated with the half-lives of any known elements. However, Moody told us, he and his Dubna colleagues ran a consistency check on the relation between the observed lifetimes and their measured energies.

Running hot and cold

An alternative approach to the hot fusion method of producing superheavy elements—cold fusion—was pioneered by Oganessian in the mid-1970s. It has subsequently been used by the heavy element group at the Laboratory for Heavy Ion Research (GSI) in Darmstadt, Germany, which is now headed by Sigurd Hofmann. GSI holds undisputed claims on five of the last six elements, 107–109 and 111–112 (see PHYSICS TODAY, May 1997, page 52).

The GSI approach is to use a heavier projectile and somewhat lighter target, with energies chosen so that the compound nucleus is formed with relatively little excitation energy. GSI's program is to proceed systematically from one element to the next, charting the way by noting cross sections, lifetimes and so forth, and making predictions about each new step. For example, their 1996 discovery of $^{277}112$ was based on a single nucleus, but the isotope decayed by a chain of six alpha emissions, each time to a nucleus whose characteristics were well known.

Hofmann and his colleagues tried last March and April to produce element 113 by firing a zinc-70 beam onto a bismuth-209 target. They found no candidates in a total of more than 46 days running, placing an upper limit of less than one picobarn on the cross section.

The recent experiments at both Dubna and GSI, in which over a month's worth of data yielded at most a single event, underscore the difficulty that such efforts now face—the extremely low cross sections. According to Peter Armbruster, Hofmann's predecessor at GSI, the cross sections get lower as the atomic numbers get higher. At one picobarn, detectors at all three labs—GSI, Berkeley, and Dubna—are bumping up against their limit of sensitivity. So even as nuclear physicists salivate at the prospect of reaching the island of stability, they may have to curb their appetites until higher currents or steadier beams become available.

BARBARA GOSS LEVI ■