Berkeley Lab Leapfrogs to Elements 116 and 118

> The discovery of two new elements where none had been expected gives nuclear physicists hope of exploring hitherto inaccessible regions of the nuclear chart.

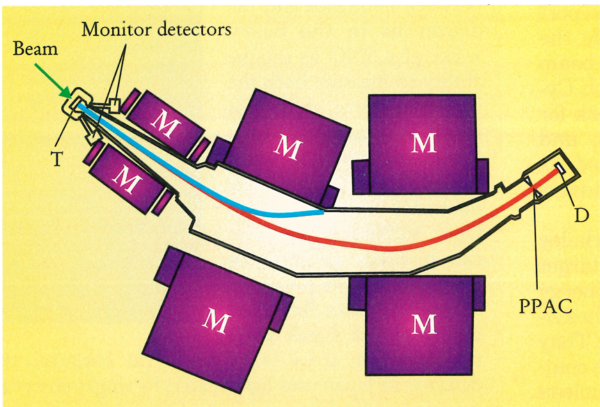
If nuclear physicists were surprised last January by a reported sighting of element 114, they were utterly floored by a recent report of elements 116 and 118.[1] No one had thought that these two were worth looking for with today's accelerators. No one, that is, except theorist Robert Smolańczuk of Warsaw's Andrej Soltan Institute for Nuclear Studies, who had calculated that certain reactions can generate isotopes of elements 116 through 119 with cross sections orders of magnitude greater than expected.[2] Researchers at Lawrence Berkeley National Laboratory, where Smolańczuk is currently a Fulbright scholar, took a chance that he was right and set up the prescribed experiment for producing the new element ^{293}118 (and its daughter ^{289}116). They found three candidates in 11 days.

The three atoms seen at Berkeley have decay halflives of a few hundred microseconds. By contrast, the single candidate for element 114, found by researchers from the Joint Institute for Nuclear Research in Dubna, Russia, and from Lawrence Livermore National Laboratory, hung around for 30 s, raising hopes that it is in the vicinity of the long-sought island of stability (see PHYSICS TODAY, April 1999, page 21). The far shorter halflives and lower ratio of neutrons to protons in the newly seen elements 116 and 118 indicate that these isotopes lie far offshore. They are remarkable for the very fact that they could be seen. Perhaps many more such superheavy isotopes can now be generated and studied.

Confounding expectations

Before the recent sightings of elements 114, 116, and 118, heavy-ion researchers—especially those at the Laboratory for Heavy Ion Research (GSI) in Darmstadt, Germany—had made steady progress in synthesizing elements with atomic numbers Z up to 112, proceeding fairly systematically up the periodic table.[3] But the going was getting tough, because with each increase of one in atomic number, the production cross section dropped by a factor of three to five. By that rule, element 114 should have a cross section of a few tenths of a picobarn, which is pushing the capability of the three accelerator centers (at Berkeley, Dubna, and GSI) capable of producing superheavy elements. (A barn is 10^{-28} m^2.) Elements 116 and 118 were thought to have cross sections on the order of 0.01 pb, well out of reach of existing facilities without major modifications to them. "It seemed like a rock-solid trend," commented Kenneth Gregorich, who, with Victor Ninov, led the Berkeley experiment.

The six elements 107 through 112 have been synthesized with the method of cold fusion, in which the compound nucleus formed by the collision of a nuclear projectile with a heavy nuclear target has an excitation energy of only 10–15 MeV. The compound nucleus emits one or perhaps two neutrons, resulting in the final product, often called the evaporation residue. Yuri Oganessian of Dubna had proposed cold fusion reactions in the mid-1970s, reasoning that one should be able to fuse nuclei at lower excitation energies by using the doubly magic nucleus, lead-208, as a target. (In doubly magic nuclei, both the neutron and proton energy levels are fully occupied.) To produce the isotope ^{293}118, Smolańczuk prescribed a reaction involving not only the doubly magic ^{208}Pb target but a magic projectile, krypton-86, as well. He calculated that a 449 MeV krypton beam should yield a cross section for ^{293}118 of 670 pb. The value actually measured in the recent Berkeley experiment was more than 300 times lower, specifically 2.2 (+2.6, −0.8) pb. Still, it was perhaps 1000 times higher than had been expected by extrapolating from the cross sections measured for elements up to 112.



GAS-FILLED SEPARATOR was completed just in time for a team from Lawrence Berkeley National Laboratory to detect new elements 116 and 118. Krypton-86 ions enter from left and strike a lead-208 target (T). After fusion, some compound nuclei emit a single neutron to become ions of the isotope ^{293}118. These ions undergo charge-changing collisions with the gas in the separator. Strong bending magnets (M) separate other ions present (blue path) from the ^{293}118 ions (red beam), which then pass through the parallel plate avalanche counter (PPAC) and become embedded in an ion-implanted silicon detector (D). (Adapted from ref. 1.)

Smolańczuk formulated a model to compute the optimal excitation energy for cold fusion reactions and the resulting production cross sections. In his model, the cross section is proportional to the product of two very low probabilities: the probability of fusing the projectile and target to form the compound nucleus and the probability that the compound nucleus will decay by emission of a neutron rather than by fission. Smolańczuk told us that, if anything, the survival rate that he calculates is lower than others would predict. But he comes out with a higher probability that the compound nucleus will be produced.

Smolańczuk's model considers the case that the projectile tunnels quantum mechanically into the target nucleus. He takes all but two of the parameters in his model from the standard literature; he adjusts the remaining two to fit a measured formation cross section of an isotope of nobelium and the survival probability of several compound nuclei with atomic number 102. Although he admits that he uses an abrupt cutoff in the Coulomb barrier (which hinders fusion), he

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finds that his model fits the data better than physically more realistic models. The systematic data on superheavy elements measured at GSI over the past five years were very useful in fine tuning Smolańczuk's model. His model reproduces within a factor of two the cross sections for a number of nuclei synthesized at GSI. Theorists are already working to try to understand the success of this simple model and how the more sophisticated approaches might be modified.

Serendipitous timing

Smolańczuk's predictions stood in stark contrast to the prevailing expectations. Why, then, did the Berkeley experimenters bother to test them? Such tests had not been in their plans six months earlier; rather, they had been gearing up to confirm the report of element 114. While they made the necessary preparations, however, beam time was available on the 88-Inch Cyclotron. They used the time to look for element 118. Ninov, Gregorich, and their colleagues were as amazed as everyone else when three candidates were seen in two runs.

For the experiment, the Berkeley experimenters struck a ^{208}Pb target with ^{86}Kr ions accelerated to an energy of 459 MeV. These ions were the heaviest projectiles they had ever used. They looked for reactions in which the compound nucleus emitted a single nucleon and subsequently decayed by a chain of alpha decays. They found three chains of six alpha decays; in each chain, the decays all occurred within a small region on the detector, as one would expect for a chain of descendants from the same parent nucleus. If the researchers are correct in their identification of the residual nucleus as ^{293}118, the other isotopes in the chain are ^{289}116, ^{285}114, ^{281}112, ^{277}110, ^{273}108, and ^{269}106. None of these isotopes has been produced before. More experiments will be needed to confirm these results.

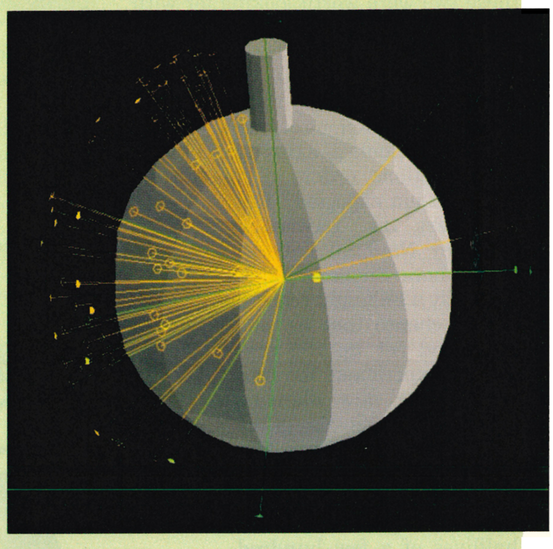
The experiment marked the debut of Berkeley's new gas-filled isotope separator, built to give the lab higher efficiency and greater background suppression for superheavy element production (see the figure on page 17). The researchers were looking for reactions in which the compound nucleus, formed by colliding ^{86}Kr ions with the ^{208}Pb target, decayed by emitting a single neutron. Such residual ions recoiled into the separator, where charge-changing collisions with the gas molecules brought them to an average charge state. Strong bending magnets separated out any beam ions or transfer reaction products (blue path). The residual nuclei of interest (red path) passed through a parallel plate avalanche counter and became embedded in an ion-implanted silicon detector. Correlations between the PPAC and the detector helped distinguish two types of events: those associated with an atom flying through the separator and those resulting from the decay of atoms already embedded in the detector.

Ninov, who spent 11 years at GSI before going to Berkeley, told us that the Berkeley group got tremendous support from his former GSI colleagues, who couldn't undertake their

First Events Seen at Sudbury Neutrino Observatory

Fifteen years after it was initially proposed, the Sudbury Neutrino Observatory (SNO) has begun collecting data on solar and atmospheric neutrinos. Built by a collaboration of scientists from Canada, the US, and the UK, SNO is the second of a new generation of powerful neutrino detectors (see PHYSICS TODAY, July 1996, page 30 and December 1997, page 56). It consists of an acrylic container holding 1000 metric tons of heavy water, surrounded by an array of about 9600 photomultiplier tubes (PMTs) in ordinary water and buried 2 km underground in a nickel mine near Sudbury, Ontario.

Reconstructed here is one probable solar neutrino event recorded at SNO. Seventy-five PMTs (yellow hexagons) detected the Čerenkov radiation emitted by an electron that was produced when a neutrino collided with the heavy water (gray sphere). The yellow lines show the inferred photon paths from the calculated location of the neutrino strike to the PMTs.



Two different reactions between neutrinos and the deuterons in the heavy water give SNO its unique ability to measure both the flux of electron neutrinos from the Sun and the total flux of all solar neutrinos, including muon and tau neutrinos. An electron neutrino striking a deuteron can produce an electron through $d + \nu_e \rightarrow p + p + e$. Any of the three flavors of neutrinos can break apart the deuteron: $d + \nu \rightarrow p + n + \nu$. (In contrast, the Super Kamiokande neutrino detector in Japan uses light water; its single observable reaction—elastic scattering of neutrinos off electrons—is sensitive primarily to electron neutrinos but cannot distinguish between neutrino flavors. Super Kamiokande has recently begun detecting neutrinos produced by the KEK proton accelerator—see page 9 of this issue.)

"By comparing the measurements of the two reactions," explains SNO director Art McDonald of Queen's University at Kingston, "we can know whether all of the solar neutrinos striking the detector are electron neutrinos or whether some of them have changed to another flavor." Because only electron neutrinos are produced in the Sun, such information is key for solving the "solar neutrino problem," the name given to the observation by earlier neutrino detectors of a solar neutrino flux that was much less than expected.

Muon and tau neutrinos can also be produced in the atmosphere by cosmic rays. Such atmospheric neutrinos will have much larger energy, however, and will be readily distinguishable from solar neutrinos at SNO. In addition, the event rate for atmospheric neutrinos should be significantly smaller—only a few hundred per year, compared to between 10 and 20 solar neutrino events per day above SNO's threshold of about 5 MeV.

To prevent distortion of the spectra recorded from neutrino events, keeping the detector free of radioactive contamination was a major focus throughout construction. "The radioactive background is where we hoped to have it at this stage," McDonald told us. Natural decay and the continuous purification of the water are expected to reduce the background even further.

In future experiments, SNO will employ two additional detection mechanisms—an array of detectors filled with ^{3}He and placed inside the heavy water, and magnesium chloride salt dissolved in the water—for better sensitivity to the neutrons produced in the deuteron dissociation reaction.

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own experiment at the time because upgrades were being made on their accelerator and separator. But the GSI team provided Berkeley with some material, such as a target wheel and silicon detectors, and shared the experience they had gained with a recoil separator and various correlation techniques. By the time that members of GSI's heavy ion group heard of Berkeley's results, they were able to get 8.5 days of beam time for an attempt at confirmation. In that time, they saw no candidates for ^{293}118. If the run had yielded a single atom, the production cross section would be 1.6 pb, Hofmann told us. He and his coworkers have set an upper limit of 2.8 pb, a value that falls within Berkeley's uncertainty range. They are planning to try again as soon as possible.

Buoyed by the unexpected success, the Berkeley group may go on to explore other predictions by Smolańczuk, possibly the reaction of rubidium-87 projectiles on a ^{208}Pb target to produce ^{294}119. Although testing some of these newly promising reactions has moved up on their priority list, the Berkeley experimenters still plan to look for element 114, as a check on the Dubna results. To do that experiment, the Berkeley team needs to develop the means to handle the radioactive target (plutonium-244) and increase the efficiency of their ion beam source because the target projectile (calcium-48) is so rare. **Barbara Goss Levi**

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Space Telescope Key Project Completes Task of Measuring the Hubble Constant within 10%

Five years before the Hubble Space Telescope was launched in 1990, NASA designated a "Key Project" for the orbiting telescope. The project's goal was to pin down the Hubble constant H_0 to within 10%. At the time, H_0, a fundamental cosmological parameter that measures the universe's present rate of expansion, was uncertain to within a factor of two. Estimates ranged from 50 to 100 km/s per megaparsec. (Hubble's law of universal expansion asserts that, at cosmological distances, recessional velocity is proportional to distance; 1 Mpc is about 3 million light-years.)

The Hubble constant is crucial to the calculation of the age of the universe, its geometry, and the abundance of the light elements produced in the first few minutes after the Big Bang. The more tightly one can pin down the key observational parameters, the more stringently one can test cosmological theories.

At the recent centennial meeting of the American Astronomical Society in Chicago, the HST H_0 Key Project team, headed by Wendy Freedman (Carnegie Observatories), Robert Kennicutt (University of Arizona), and Jeremy Mould (Australian National University), announced that the task had been successfully completed. The team reported[1] a Hubble constant of 71 ± 7 km/(s Mpc).

One determines H_0 by observing the Doppler recessional velocities of distant objects and then measuring their distances by means independent of redshift. At the heart of the HST H_0 Key Project was the determination of the distances to 18 galaxies—out to 25 Mpc—by measuring the periods and apparent luminosities of almost 800 Cepheid variable stars in them.

> By measuring hundreds of periodically varying stars out to 80 million light-years, the Hubble telescope has calibrated much brighter cosmological yardsticks that we can see billions of light-years away.

Cepheids are very bright young stars, found mostly in spiral galaxies, whose luminosities vary cyclically, with periods on the order of days or weeks. Because one can deduce the intrinsic luminosity of a Cepheid with impressive precision from its period, Cepheids have become the primary yardsticks for extragalactic distances. The more Cepheids one can measure in a given galaxy, the smaller is the statistical uncertainty of the distance to that galaxy.

But even the Hubble telescope can't find and measure Cepheids much farther away than 25 Mpc. (When the HST was still on the drawing board, the frugal downsizing of the primary mirror's diameter was halted at 2.4 meters, because that was thought to be the minimum size for adequately measuring Cepheids in the important Virgo cluster of galaxies, whose center is about 17 Mpc away.) So, for purposes of determining H_0, the Key Project Cepheid distances serve primarily to calibrate more luminous secondary yardsticks, such as Type Ia supernovae and rotating spiral galaxies, that are still visible at the much greater distances where non-Hubble random and streaming velocities are presumed to be negligible.

Challenges

Almost before the applause had died down at the June AAS meeting, two other groups reported divergent results that appeared to challenge the Key Project result. In a novel use of very-long-baseline interferometry, a National Radio Astronomy Observatory group reported[2] a purely geometric measurement of the distance to a galaxy some 8 Mpc away with an uncertainty of only 4%. But that radio-interferometry distance appears to be 15% less than the Cepheid distance to that same galaxy (NGC 4258) recently measured by Eyal Maoz (NASA Ames Research Center) and coworkers.[3] This would suggest that the Key Project's H_0 might be too small by 15%.

However, an even more recent very-long-baseline radio measurement, by Norbert Bartel (York University, Toronto) and coworkers, of an expanding Type II supernova shell in the galaxy M81, only 4 Mpc from us, yields a geometric distance that agrees very well with the Key Project's Cepheid distance to M81.

At the other extreme, claiming that the Key Project's Hubble constant is too big by 18%, was a not unexpected report[4] from Allan Sandage (Carnegie Observatories) and coworkers, reporting an H_0 of about 60 km/(s Mpc). Sandage and company have, for many years now, been holding out for a significantly smaller Hubble constant, and hence an older universe, than most other workers in the field. They base their result on their calibration of Type Ia supernovae. They used the Hubble telescope to measure Cepheid distances to the very few galaxies within 25 Mpc for which there are historical measurements of Type Ia explosions—going all the way back to the year 1895. But whereas Sandage's group used Cepheids only to calibrate Type Ia supernovae, the Key Project bases its determination of the Hubble constant on the Cepheid calibration of three