# GSI: Heavy-Ion Research as the Future of Nuclear Science

Fields of science seem to go through cycles of intellectual fortune, which are often linked to advances in experimental techniques.

Nuclear physics began with the discovery of radioactivity in 1896, and progressed slowly through the first quarter of the 20th century before accelerators were available. Then it burst forth in the 1930's, when three great discoveries—the neutron, antimatter, and fission—were made. After World War II, many more data were obtained from an increasing number of laboratories using new cyclotron and Van de Graaff accelerators. By the mid-1950's, the most important phenomena had been categorized, and the basic models used to understand the nucleus had been expostulated.

The last two decades can be viewed as a plateau in the history of the field, but before 1980 a new generation of accelerators should begin to illuminate a class of nuclear phenomena that has barely been touched on. Among the new accelerators, the first and the one that promises to be the best for many years is a machine that is now beginning operation in southwest Germany near Darmstadt. The $60 million facility will accelerate heavy ions, which may be more than 200 times heavier than the most common probe of the nucleus, the proton. Referred to by the acronym GSI (Gesellschaft für Schwerionenforschung), the new laboratory (Fig. 1) is a national center for research, enjoying generous funding and considerable prestige as one of the 12 "big science" centers in West Germany.

While it may not be the case that the whole field of nuclear physics is "in the afternoon of its life," as the principal figure behind the organization of GSI, Christoph Schmelzer, said in an interview with *Science*, there is strong support in many countries for the idea that the best opportunity for a renaissance will be the exploration of the phenomena induced by very heavy particles.

That was the implicit message from the 1975 Nobel laureates in physics, Aage Bohr, Ben Mottelson, and James Rainwater, when they spoke in Washington recently, and it is the rationale behind new heavy-ion accelerator projects now under way in the United States, France, the Soviet Union, Great Britain, and Japan, as well as West Germany.

At the spring meeting of the American Physical Society, Aage Bohr pointed out that the ability to accelerate heavy ions is a new opportunity, and Ben Mottelson focused on heavy-ion experiments almost exclusively in discussing new prospects in nuclear studies. These two residents of Copenhagen, who are regarded as the deans of the field of nuclear physics by researchers around the world, received the prize along with Rainwater for collective models of fairly small nuclear excitations, generally induced by protons or other light particles. Mottelson noted that some people say accelerator experiments have heretofore only "tickled" the nucleus. By contrast, heavy-ion interactions could produce very large excitations that have not been studied before. Another example of a new type of interaction that can occur between heavy-ions is a grazing collision, in which two heavy nuclei briefly stick together and produce a very high degree of angular motion, perhaps throwing off neutrons and protons when the spin can no longer be counterbalanced by the nuclear forces. The most important phenomena found at a new accelerator are seldom the ones it was built to investigate, so Mottelson cautioned that, as the Danes say, it is very dangerous to predict, especially about the future.

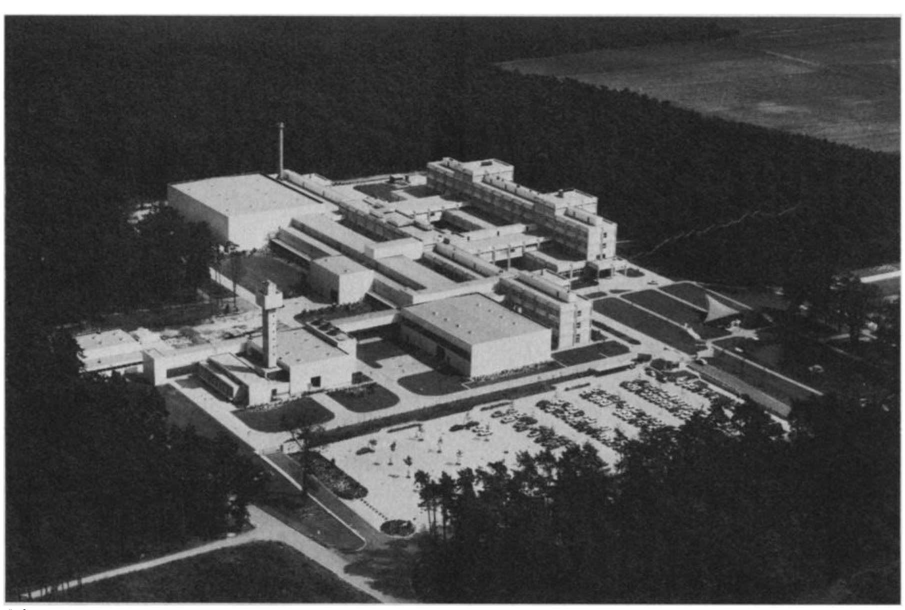

Fig. 1. The new GSI laboratory for heavy-ion research near Darmstadt, Germany. The buildings were completed in 1974, and the accelerator itself, which is installed in the tunnel between two large halls on the left, should be completely operational by the end of the summer.

### First to Accelerate Uranium

Improvements in small accelerators have enabled them to produce beams of ions up to the mass of oxygen (16) or perhaps sulfur (32). The new heavy-ion machines will pick up at that point, and produce even more massive ions, from argon (40) up to the heaviest natural elements. To be accelerated effectively, atoms must be stripped of some of their electrons, making them positively charged ions—hence the name heavy ions. Different accelerators will vary considerably in the energy they impart to the beam of heavy-ions. It depends on the amount of radio-frequency (RF) power the accelerator can apply to the particles and their degree of ionization—for many accelerated atoms up to half of the electrons are stripped off. Getting a high degree of ionization is perhaps the biggest technical problem in heavy-ion research.

The best energy measure is not the total energy of the ions but the amount of energy per mass unit, which is an accurate indicator of the velocity needed for two positively charged nuclei to overcome the forces of electrical repulsion. When the GSI accelerator reaches full-stage operation, probably at the end of this summer, it will boost its beams to an energy of 10.2 million electron volts (Mev) per nucleon, which is equivalent to a velocity of about 40,000 kilometers per second. The threshold to overcome nuclear repulsion is about 6 Mev per nucleon for heavy ions.

Not all the final accelerating cavities for the GSI accelerator, which is called the Unilac, have been commissioned yet, so the maximum energies have not yet been reached but the Unilac has already produced beams of argon, krypton, and xenon up to 7.6 Mev per nucleon, and successfully produced a beam of fast uranium ions (mass 238), something that no other accelerator had done before. Producing uranium-uranium collisions has been a goal of heavy-ion researchers for years, because uranium is the heaviest natural element. On 1 April, the Unilac accelerated a uranium beam to an energy of 6.6 Mev per nucleon. The total energy, for the 238 constituent nucleons of uranium, was 1.4 billion electron volts (Gev), which approaches the range of high-energy accelerators. But the speed of the heavy-ion beam, being about 10 percent of the speed of light, did not approach that of the high-energy accelerators.

Before the GSI facility began operation, the two major centers for heavy-ion research were the laboratories that have produced most of the man-made transuranic elements, Lawrence Berkeley Laboratory of the University of California, and the Laboratory for Nuclear Reactions at Dubna in the Soviet Union. In the last year or so these two facilities have accelerated ions as heavy as xenon (mass 124 to 136), although not without considerable difficulty. More routinely, they accelerate ions of krypton (mass 84) or lighter elements. The Berkeley accelerator is a linear machine, called the SuperHILAC, that can attain energies of 8.5 Mev per nucleon. The Dubna machine is a pair of cyclotrons, 2 and 3 meters in diameter, that can reach an energy of 7 Mev per nucleon for xenon.

The two transuranic element factories have been preeminent for almost two decades, occupying unique positions in the world of physics research, but they are now growing middle-aged. One knowledgeable American nuclear scientist says that the new German center will make the two older labs "relatively obsolete both from energy and intensity viewpoints." Of course, it may take some time for the GSI staff to learn how to get all that was intended from their accelerator, but if it works well, says Albert Ghiorso at the Berkeley SuperHILAC, "they may beat us."

The GSI laboratory is a limited liability company, founded in 1969, and wholly owned by the Federal Republic of Germany and the Land of Hesse, in which it is located. As with other big science centers, both the federal government and the state contribute to the support of the laboratory, in the ratio of 9:1. The total cost of GSI will be $63 million—about $20 million for the accelerator itself. For the preparation of the site, the Land of Hesse contributed additional money and reportedly requested that the buildings be made as versatile as possible. The ion source room, the accelerator tunnel, and the big experimental bays are separate structures, only loosely connected with the two general-purpose buildings used for offices, work space, and secondary laboratories. If future research patterns suggest that a different sort of institute is preferable, most of the present structures could be used.

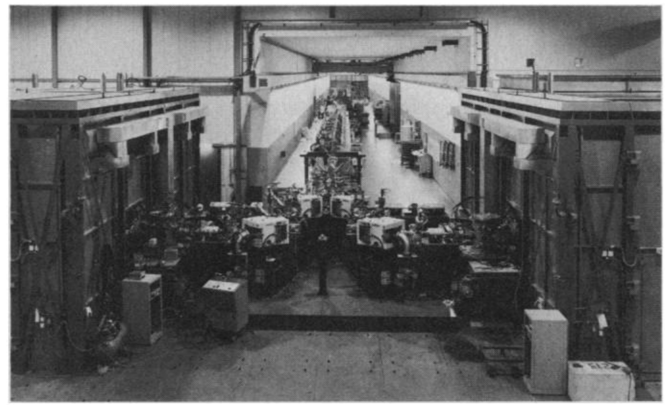

Fig. 2. View down the length of the GSI linear accelerator, showing the two enclosed rooms on right and left where ions are produced. From either source room, the beam is bent by magnets in the foreground to the proper trajectory for injection into the accelerator sections, in the tunnel behind. Two ion sources give increased reliability.

As a place to do research, the laboratory is bright, comfortable, and accentuated with red, orange, yellow, and green walls and doors. Even the accelerator is color-coded for clarity and levity, with functionally different sections a different hue. One accelerator tank is a delightful purplish color that is called "blueberries in cream." The grounds are also pleasant, with a large kitelike sculpture and a small pond in the courtyard.

In choosing a site for the heavy-ion research center, one of the requirements was that it be easy to reach from various parts of the country, and GSI is, in fact, less than an hour away from the major transportation center at Frankfurt by car or train. The principal users of the new center will be West German scientists, according to Rudolf Bock at GSI, but many foreign scientists will also participate. One group from Copenhagen is already doing experiments, and many foreign researchers will join as members in existing groups. The scientific directors of GSI are Bock, who came from the University of Marburg; P. Armbruster, from the government nuclear research center at Jülich; G. Herrmann, from the University of Mainz; and Schmelzer, from the University of Heidelberg. The areas they generally oversee are nuclear physics, atomic physics, nuclear chemistry, and accelerator development.

The laboratory is still young. The decision to build it was made in 1969 and the construction started in 1971. Buildings were completed in June 1974, so they have been occupied for only about 18 months. The GSI directors were able to retain their own architects for rapid planning, and the capital funding for the laboratory has been prompt. While the laboratory staff was overseeing the task of constructing the buildings and the accelerator, the university scientists took a large part in the design, assembly, and testing of most of the major pieces of experimental equipment. The active participation of outside scientists from more than a dozen universities and research institutes is one reason GSI has risen so swiftly.

### The Plan for the Unilac

Another important reason for the rapid development of the laboratory is that the accelerator design was complete ahead of time. Since 1961, a group of physicists working under Schmelzer at Heidelberg had been testing various designs for a new heavy-ion accelerator. The plans were "pretty firm" by 1964, and a study group of 40 completed the design by 1968. By the time GSI was formed, the management led by D. Böhne could immediately start ordering the parts for the new machine.

The best way to assemble a high-performance heavy-ion accelerator is vigorously disputed, and nearly every country has a different way of doing it. The West German machine, like the SuperHILAC, is a linear accelerator. The French plan to use two cyclotrons, one injecting a beam into the next. The British will use a very large Van de Graaff accelerator, and the Americans will use a Van de Graaff to inject a beam into a cyclotron. Among the approved projects, the French one, named GANIL and planned for a site at Caen in Normandy, appears to be the stiffest competition for the Darmstadt project.

When drawing up plans for the Unilac, "we continually tried to shoot down our plan for a linear accelerator," said Schmelzer, "but it kept coming back as the answer." The Heidelberg group studied cyclotrons quite thoroughly and found they had problems, "though technically solvable problems, I admit," said Schmelzer. Cyclotrons need a better vacvacuum inside, since the path length of the beam orbiting many times through the circular cyclotron is greater, and extracting the beam can be difficult because the last few orbits are close together.

The Unilac is virtually a compendium of different types of linear accelerator inventions. It divides into three stages. The first uses a Wideroe type device, the second an Alvarez type, and the third a single-gap type. Each is a slightly different method for propelling charged particles with a high voltage electromagnetic field oscillating at radio frequency. Electron stripping occurs after the Wideroe.

The beam is produced in one of two ion sources (Fig. 2) and then injected into the Wideroe structures (Fig. 3). Four of these in series boost the energy to 1.4 Mev per nucleon. At that energy, many more electrons can be knocked off by passing the beam through a stripper. For example, the argon beam starts out with charge + 2 (two electrons removed) and is further stripped in gas to charge + 10. The uranium beam starts with charge + 10 and is stripped in the carbon foil to a charge + 41.

The stripper planned for routine use is a supersonic nitrogen jet, passing through the beam with enough speed that it is easily caught and pumped away on the other side without reducing the vacuum. A carbon foil stripper can be used to reach higher final energies, but the foils break easily. Actually four or five different charge states are produced by the stripper, and a sequence of magnets selects the most abundant one for further acceleration and deflects another one into a low-energy (1.4 Mev) experimental area for atomic and solid state experiments.

After the beam is highly stripped, two more stages boost it to the final energy. A pair of Alvarez structures, of the sort used on many proton linear accelerators, raise the energy to 5.9 Mev per nucleon. Then a long series of single-gap cavities, properly phased for the still accelerating beam, produce the final energy, which is designed to be 8.5 Mev per nucleon with the gas stripper and 10.2 with the foil stripper. (The energies noted are for a uranium beam, and tend to be higher for the lighter ions). Of the 20 single-gap cavities, 8 are now in place, and the rest should be installed by mid-September, according to Norbert Angert, head of the accelerator operation.

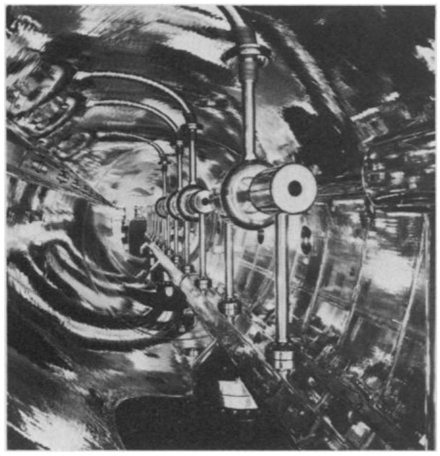

Fig. 3. The inside of one of the Wideroe sections. The vertical stems hold drift tubes through which the ions pass. Myriad reflections can be seen in the polished copper walls, and the room behind the tank is visible at the far end.

The Unilac design is characterized by American researchers as one that does not take huge steps in accelerator technology and that puts a high premium on reliability. The three types of RF stages are old inventions that have been matched well to the different requirements encountered as the beam increases in speed. Two ion sources will make the accelerator much more reliable, since sources tend to burn out every 40 hours or so.

Making a source for certain types of heavy-ions is such a difficult job that it is often the limiting factor in the operation of a heavy-ion accelerator. The accelerator group at GSI has done extensive development of duoplasmatron (for ions up to mass 130) and penning sources (for the heaviest ions), and the achievements, measured in terms of the current for each ion type, are outstanding. "Their ion sourcery is the equal of anyone's," says John Martin at the Oak Ridge National Laboratory in Tennessee.

At the present time, both Alvarez structures are operating, with an extra stripper between to boost the energy slightly, and the GSI staff is doing phasing necessary to use the single-gap cavities. The only significant problem that has arisen so far is with the Alvarez RF power supplies, which seem to burn out if they are operated at the fully specified level. To improve their reliability, GSI is now planning to operate the power supplies at a reduced power rating. More power supplies to compensate for this derating are being installed.

Less than the optimum amount of RF power would not affect the accelerator's performance with medium-mass ions, but for the heaviest species, such as uranium, a power handicap would reduce the accelerator's duty factor (percentage of the time the beam is actually "on" each second). It would not affect the energy, however. The total power drawn from the electrical mains by the whole accelerator, when all stages are operating, is expected to be about 6 megawatts.

For many years the cherished goal of heavy-ion research has been to produce superheavy elements—predicted to be stable new atoms with a charge of about 114 and a weight of about 300. Such a finding would almost guarantee its discoverer a Nobel prize, so many researchers, including some at GSI, are looking for them. But there is growing evidence that superheavy elements may be very hard to produce, and the areas singled out for study are now much more diversified.

One of the more unusual experiments planned is a test of quantum electrodynamics (QED) in the environment of a very strong electric field. When the nucleii of two heavy-ions approach each other the fields produced by the combined charges may be as much as four times stronger than those produced in natural elements. Such strong fields may alter the properties of the vacuum state described by QED theory. Specifically, although the vacuum is predicted to be electrically neutral, the theory predicts that in a very strong field the innermost K-shell electron energy may be depressed enough so that it becomes part of a continuum of negative energy states, sometimes called the Dirac electron sea. Predicted to occur when the combined charge ($Z$) is about 170, the phenomenon would liberate a positron. Two new magnetic spectrometers at GSI have been specially designed to trap such positrons. One is called an orange spectrometer, and the other is a solenoid spectrometer. Other unusual physical effects that appear to be precursors to positron emission have already been seen in quasimolecular x-rays of colliding heavy-ions and will be further studied at GSI.

Whether or not superheavy elements are produced, there is no doubt that the German accelerator will be an excellent tool for making new elements and exotic isotopes of known elements. The nuclear chemistry groups at GSI will be looking not only at these effects, but also at other unusual nuclear effects, such as $\beta$-delayed fission and high-spin isomerism, which produce states with lifetimes of a few minutes or more. Among their tools will be an on-line mass separator, similar to Isolde at CERN, and a powerful velocity separator. At least one group will use the mass separator, with a molten metal target, to try to find superheavies; two other groups will use thick solid targets and chemical separation techniques, to try to find superheavies on the basis of their predicted chemical properties.

The nuclear physics studies at GSI will be very broad in scope, covering not only the high-spin states and the high-energy excitations mentioned by the Nobel laureates, but also testing the interaction mechanisms of very heavy-ions when they hit each other. Studies at Berkeley have already shown that a type of prompt interaction that was little noted with lighter ions tends to dominate the reactions of heavy-ions. Called deep inelastic scattering, the process appears to be the passage of the lighter ion straight through the heavier one, exchanging perhaps 5 to 25 nucleons as it goes by, but not fusing to form a composite system. When uranium was bombarded with argon-40, a composite system was formed half the time. With a projectile twice as heavy, krypton-84, fusion occurred only about 4 percent of the time.

It is considered that only a fusion reaction, and a very special type at that, could produce a superheavy stable nucleus. So in the face of unsuccessful searches so far, and a trend in the reaction mechanism that suppresses fusion, most nuclear scientists are now somewhat pessimistic about the possibility of making them with accelerators. As Ben Mottelson said in Washington, "People are convinced they are there, but all the reactions that have been studied so far produce them in such small numbers that it will be very hard to detect them."

Many scientists have also searched for evidence of the superheavy elements in nature, and Edward Anders and his colleagues at the University of Chicago have reported evidence of fission products from a superheavy element ($Z$ near 114) in the Allende meteorite [*Science* **190**, 1262 (1975)].

### Technical Excellence

In a world where low-energy nuclear physics was long ago overshadowed by the size and power of high-energy physics, the scale of GSI is startling. Most nuclear physics laboratories are fairly small facilities, designed to serve a small group of scientists. But GSI is being planned as a national facility. The best comparison in the United States would be with a high-energy physics laboratory. There are 400 people on the staff of GSI, including 200 technicians and support personnel who make up the "accelerator infrastructure." The scientific staff is now 40, including 8 accelerator physicists. With a yearly operating budget that is now \$20 million and is not expected to fall below \$16 million even after construction is completed, the funding for GSI is at least four times that of the Berkeley SuperHILAC laboratory (\$4 to \$5 million per year), and only slightly less than that of the Stanford high-energy accelerator.

To a visitor to the GSI laboratory, its technical sophistication is obvious. Almost every bit of equipment incorporates the latest development, whether in electronics, computers, or custom-made experimental instruments. The laboratory has two computers, an IBM 370-168 and a Sigma 6, for batch processing, on-line data analysis, and eventually computer control of the accelerator. Presently ten programmers are working on the accelerator control system, which will continually take diagnostic data from five satellite minicomputers to control the operation of the Unilac. This is particularly important for a heavy-ion machine, because the sources are continually changing as the exit orifice erodes away, and tuning and focusing the accelerator is different for every isotope, ion and energy. The accelerator is being run under manual control now, and computer control will begin in late 1977.

A nice example of the technical adroitness of the Unilac is the method used to control the ion sources, which cannot be wired to the outside because the 250-kilovolt potential for preacceleration would cause shorts. Older accelerators have used fishline, glass rods, and various other homemade inventions to stretch safely across the large voltage drop, but the Unilac uses a glass fiber optic cable. The glass is, of course, an insulator, and the data transmission cable will allow direct control of the source by computer.

Technical competence is only one of many ingredients that go into the successful operation of a research enterprise, but it is an indispensable ingredient. Until the early 1980's, when the new French project is scheduled to be working, GSI should have the premier facility for heavy-ion reserach. No one knows what new things will be found, but with as fine a facility as the Unilac, the West Germans have a good chance of finding them.—WILLIAM D. METZ

# Mathematical Proofs: The Genesis of Reasonable Doubt

Mathematicians have known for 40 years that infinitely many statements in mathematics are undecidable—that is, their truth or falsity can be neither proved nor disproved. This disquieting result had a profound philosophical impact on mathematicians because it imposed a barrier within mathematics itself to the formerly invincible methods of proof. Yet gradually mathematicians came to accept and live with this result and to believe, as an act of faith, that showing a statement is decidable is tantamount to showing it can be proved. Now, however, a new twist to this undecidability question has come up. Investigators are finding that even theoretically decidable questions may have proofs so long that they can never be written down, either by humans or by computers.

To circumvent the problem of impossibly long proofs, Michael Rabin of the Hebrew University in Jerusalem proposes that mathematicians relax their definition of a proof. In many cases it may be possible to "prove" statements with the aid of a computer if the computer is allowed to err with a predetermined low probability. Rabin demonstrated the feasibility of this idea with a new way to quickly determine, with one chance in a billion of being wrong, whether or not an arbitrarily chosen large number is a prime.* Because Rabin's method of proof goes against deeply ingrained notions of truth and beauty in mathematics, it is setting off a sometimes heated controversy among investigators.

Rabin became convinced of the utility of a new definition of proof when he considered the history of attempts to prove theorems with computers. About 5 years ago, there was a great deal of interest in this way of proving theorems. This interest arose in connection with research in artificial intelligence and, specifically, in connection with such problems as designing automatic de-bugging procedures to find errors in computer programs. Researchers soon found, however, that

*Rabin presented this result at the symposium on New Directions and Recent Results in Algorithms and Complexity, held at Carnegie-Mellon University in Pittsburgh on 7 to 9 April 1976.