Accelerator at Batavia: The Next Step in High Energy Physics

In a period of stagnating research budgets in many areas of science, the National Accelerator Laboratory (NAL) near Batavia, Illinois, stands out as a bright prospect for high energy physicists, one which will enable them to take the next step in this increasingly expensive field of research. The construction of NAL's large synchrotron accelerator is almost a year ahead of schedule, despite funding delays, and its operation is expected to begin in mid-1971. The machine will produce protons of up to 500 Gev, more than double the energy initially planned. And although the accelerator design makes use of some sophisticated new technology, the $250-million construction costs are within the original estimates, in contrast to the cost overruns so familiar in the development of military technology. Physicists plan to use the accelerator to test current theories about the basic composition of matter and about three of the four currently known forces—the strong interaction, the weak interaction, and the electromagnetic interaction. They hope to gain new information about the structure of protons and neutrons, and they will also be looking for such hypothetical particles as quarks, intermediate bosons, and magnetic monopoles.

The NAL is headed by physicist Robert Wilson and operated by the Universities Research Association, a group of 51 universities, with funding from the U.S. Atomic Energy Commission. Although the NAL accelerator will permit experimentation at the highest energies yet achieved, it is by no means the only billion-electron-volt machine in existence. Among the major proton accelerators in operation today are the 76-Gev synchrotron at Serpukhov in the Soviet Union, the 33-Gev machine at Brookhaven National Laboratory on Long Island, and a 30-Gev machine operated by the European Organization for Nuclear Research (CERN) in Geneva. Older proton machines include the 12-Gev synchrotron at Argonne National Laboratory, the 6-Gev bevatron at Berkeley, and the 7-Gev Nimrod machine at the Rutherford Laboratories in England.

Each new generation of accelerators has allowed deeper probes into the properties of the "fundamental" particles—protons, neutrons, and electrons—and has enabled the discovery of new particles such as mesons. Because being on the forefront of research in high energy physics means having access to the most powerful machine, there have been multiple pressures for the construction of new accelerators, including prestige-laden competition between countries to build the biggest accelerator and pork-barrel conflict within countries or multinational regions (such as Europe) over where it should be located. The "life" of an accelerator, in terms of intense interest in research which can be done with its range of energies, seems to be about 10 years; thereafter the need to go to still higher energies in order to make significant progress becomes apparent. The Batavia machine is the first of a new generation of big accelerators; it will have more than six times the energy of the largest existing machine.

Accelerator Design and Construction

The NAL synchrotron works on the same principles as other electromagnetic accelerators, propelling charged particles (in this case protons) with radio-frequency (RF) electric fields and guiding them with magnetic fields. However, in contrast to the three-stage design of many previous synchrotrons, the Batavia machine accelerates particles in four stages: a 750-Mev Cockcroft-Walton machine; a 200-Mev linear accelerator (Linac) about 150 meters long; a rapid-cycling 8-Gev booster synchrotron with a radius of 75 meters; and finally a main ring synchrotron with a radius of 1 kilometer, which accelerates the protons to their terminal energy.

Protons are produced by ionizing hydrogen gas and then are given an initial shove into the Linac by the Cockcroft-Walton. The Linac, a drift-tube accelerator, takes the 750-kev protons from the Cockcroft-Walton and injects them into the booster ring at 200 Mev. The nine cylindrical tanks of the Linac contain 286 drift tubes spaced along the machine. As the protons pass between the tubes, they are accelerated by an electromagnetic wave in the form of a voltage alternating at radio frequency. Within the tubes, the protons drift, shielded from the decelerating phase of the RF field. Quadrupole-focusing magnets within the drift tubes guide the protons. The Linac achieved its design energy on 1 December 1970, exactly 2 years after construction began, to become the first operational component of the accelerator system.

The booster stage was included in the accelerator design because of the limits on the energy that can be imparted to the protons within one ring. The maximum and minimum energies available in a circular accelerator depend, for a given radius, on the range of field strengths conveniently obtainable with the magnets, which, for iron core magnets, is about 0.2 to 20 kilogauss. Hence, until superconducting magnets become available, a momentum gain of about 100 is all that can be achieved from a single ring. This gain is not enough to go from 200 Mev—approximately the highest energy feasible with reasonable cost from a Linac—to 500 Gev in a single stage. The protons in the booster ring pick up 750 kev on each circuit of the machine until they are injected into the main ring at 8 Gev. Sixteen accelerating stations are spaced around the ring, each containing a resonant RF cavity operating at about 50 Mhz. The magnets in the booster ring are of the combined function type that includes in one unit a bending field to provide the centripetal force required to guide the protons in a circular path and a focusing field to keep the protons centered in their path. Pressure in the vacuum chamber through which the protons move is maintained at 5×10^{-7} torr. The booster is a rapid-cycling machine operating at 15 pulses per second; 13 pulses, or about 0.8 second, are required to fill the main ring.

Once the main ring is filled, the protons are accelerated around the ring about 70,000 times and pick up 2.8 Mev on each revolution to reach a final energy of 200 Gev in about 1.6 seconds. The beam is then gradually extracted over a 1-second period for use in the experimental areas, so that the basic duty cycle of the machine when operating at 200 Gev is about 4 seconds. Beam intensity will be 5×10^{13} protons per pulse. The NAL staff expects, because of some good luck, to be able to operate its machine at reduced intensity with beams as high as 500 Gev. Breakthroughs in the technology of thyristors that are used as rectifiers in the magnet power supplies enabled NAL to purchase the power necessary for 500 Gev for less than the amounts originally budgeted for lower energies. The reduced intensities at higher energies will be necessary because, although the magnets will be able to generate fields strong enough to contain 500-Gev protons, the cooling equipment which is being installed now will only handle 200 Gev at full intensity. The cooling system will be upgraded later, but in the meantime some 500-Gev protons will be produced.

To facilitate maintenance, the equipment in the main ring is designed in a modular fashion. Faulty magnets can be easily replaced and removed for repair work by a specially built cart that fits into the 3-meter-diameter main tunnel. The approximately 1000 magnets spaced around the tunnel, which is 6.28 kilometers in length, are of the novel separated-function design, with the bending magnets and the quadrupole-focusing magnets being distinct units. The NAL synchrotron is the first large accelerator to use this more efficient design, which allows higher flux densities in the bending magnets and hence reduces the radius of the machine required for a given energy. Another innovation in the NAL machine is that the electrical energy used to power the magnets will be stored throughout the network of the commercial power company during the low energy part of the 4-second duty cycle rather than in mechanical systems of motor generators and flywheels, as in earlier synchrotrons.

Despite the high energies of particles produced by the NAL accelerator, radiation is not expected to be a problem within the main tunnel because the entire machine is designed to allow efficient extraction of the beam. The main tunnel includes straight sections about 60 meters long, in which the beam can be transferred into a new path by a system of electrostatic and electromagnetic septum devices. With this system the efficiency with which the beam is extracted should be better than 99.8 percent, and consequently almost all experiments will be done with targets external to the main ring. The synchrotrons at Serpukhov and Brookhaven have experimental targets that are located within the main tunnel for much of their research, and the typical extraction efficiency of external beams is only 80 percent. The subsequent radiation loss within these accelerators creates problems for routine maintenance, problems that would be aggravated at higher energies. A side benefit of NAL's improved "clean machine" design is that it requires less earth shielding above the main tunnel, with the result that construction costs are lower.

Accelerators to Examine What?

Theoretical work in high energy physics seems to have progressed to the point where further experimentation is needed to test such emerging concepts as the quark or parton models of nucleon structure and the existence of the intermediate boson, which is supposed to play a key role in weak interactions. Although there is at present considerable room for disbelief in any particular model, there appears to be consensus among enough physicists concerning the basic phenomena at issue to provide some well-defined questions for experimenters who will use the NAL accelerator. Several of these questions, as well as some of the unique problems facing high energy physicists, were discussed in talks presented last month at a symposium on particle physics at the Chicago meeting of the American Association for the Advancement of Science.

According to Victor Weisskopf of M.I.T., a peculiar difficulty that confronts physicists studying nucleons is that these particles have different ratios of excitation energy to mass from those in molecules, atoms, and nuclei. The excitation energies for molecules, atoms, and nuclei are small compared to their mass energies, so that experiments involving the excited states of these units can be performed with definite information about the number of particles present. For nucleons and mesons, however, the excitation energy approximates, and in some cases exceeds, their mass energies. Hence the traditional technique of splitting a particle by means of high energy collisions to see what it is made of does not work for nucleons, because the forces involved are so large that they create particle–antiparticle pairs in undefined numbers. This phenomenon of virtual pair production by polarization of the vacuum dominates and enormously complicates high energy processes.

The fact that nucleons and mesons are observed to have excited states is the basis, Weisskopf pointed out, for the belief that these particles are composed of smaller, more basic particles. One theory to explain the regularities observed in nucleon and meson spectra postulates the existence of quarks, which would have fractional electric charges. These hypothetical particles have a number of satisfying features, since models in which they are used can explain the observed ratio of the magnetic moment in protons to that in neutrons. Whether or not quarks exist —which will be a prime question for users of the NAL accelerator—Weisskopf stated that nucleons seem to behave in some respects as if they are a three-particle system. He also pointed out a possible analogy between nucleons and atoms; this analogy implies that the nuclear force which holds nucleons together may be a composite of more basic forces between quarks or similar particles, just as the molecular or chemical forces are derived from the electrostatic attraction between the nuclei and electrons. Weisskopf thinks that the solution of the nuclear force is the solution of nucleon structure.

Electrons are thought to be fundamental particles, but the possibility of particles with fractional electric charge raises the questions of what the basic unit of charge is and why protons and electrons have the same quanta of charge. The existence of the muon or heavy electron and of two neutrinos may imply the existence of a lepton (weakly interacting particles) spectrum, which, according to Weisskopf, would mean that the electron also has a structure and that the coulomb force is also a composite force. Physicists hope to test this possibility on the NAL accelerator.

The discovery of the magnetic monopole would complete the symmetry in electromagnetic theory by providing a fundamental unit of magnetism corresponding to the electron charge. Such a particle, once formed, would necessarily be stable, unless it recombined with another monopole of opposite polarization. Since naturally occurring monopoles have never been found, physicists assume that if they exist they must be very massive, and therefore very high energy would be required to produce them. Experimentalists plan to ascertain whether any of these monopoles are produced in the high energy proton beam at Batavia.

The existence of the intermediate boson or *W* particle is another item included on most high energy physicists' list of "standard burning questions," including that presented at the AAAS symposium by Leon Lederman of Columbia University. The intermediate boson is postulated to be a short-lived particle which plays the same role in weak interactions as does the photon in the electromagnetic interaction and the pi meson in the strong interaction. Hence the discovery of the *W* particle would settle one of the fundamental questions concerning the nature of the weak interaction. Lederman thinks it may also be possible to study pulsars, neutron stars, and gravitational collapse with the use of accelerated particles, because these astronomical phenomena appear to involve particle energies in the billion electron volt range. These possibilities and others are what seem so alluring to physicists about the energy ranges that the NAL machine will enable them to explore.

Experimental Facilities and Programs

There are three sites at Batavia in which the experimentation will be done with the high energy proton beam extracted from the NAL accelerator. The first of these is the Meson Laboratory where as many as six or seven secondary beams will be used to study strong interactions. The protons collide with a thin wire target, to produce secondary beams of protons, pions, neutrons, and neutral kaons with fluxes of about 10^6 or 10^7 particles per pulse. These beams are collimated and then allowed to collide with the experimental targets some 330 meters downrange. A variety of electronic detectors and counters are then used to monitor what comes off the target. Since the design of this area was fixed at an early date, it is limited to 200-Gev particles.

In the Neutrino Laboratory the main emphasis will be on the study of weak interactions. The protons collide with a long target and produce pi and K mesons which are allowed to decay as they travel more than 330 meters, thereby yielding neutrinos and other particles. The beam then is passed through a kilometer of earth fill to get rid of all particles other than neutrinos, which have such a small interaction probability that most penetrate the earth undisturbed. Thus experimental targets for the neutrino beam are located almost 2 kilometers from the beam extraction point on the main ring. A muon beam and a hadron beam will also be available in this area.

The third experimental facility is the Proton Laboratory. Here the full beam intensity of the accelerator can be used in elastic and inelastic scattering studies of proton-proton interactions. An experiment that will look for heavy photons will also be located in this area. The meson and neutrino areas are expected to be partially completed by this summer, when the first accelerated beam is expected from the main ring, and experiments will begin promptly. The NAL staff hopes to complete all three experimental areas sometime in 1972.

About 30 experiments have been chosen for the initial round of research from almost 100 proposals received at NAL, and a few more may be approved before this summer. Because of joint proposals as many as half of the experimental high energy physicists in the United States are involved one way or another in these initial experiments, according to the NAL staff, in addition to European and Russian participation. The philosophy represented in the initial selection of experiments favors exploration rather than quantitatively definitive measurements because physicists don't know exactly what they will find in this new energy range, according to Edwin Goldwasser, the deputy laboratory director. The idea is to maintain some flexibility, since, Goldwasser thinks, most accelerators in the past have posed new problems which were even more interesting than those that were foreseen for them.

The most glamorous types of experiments will be the searches for new particles, with quarks, intermediate bosons, magnetic monopoles, and heavy photons heading the list. But even with the enormous energies available with the NAL machine, the existence of these particles may not be definitely established. Particle energy in the center of mass system is what counts for particle production, and in the quark hunt, for example, most of the incident particle energy goes into maintaining the momentum of the center of mass in the particle plus target system. The new storage rings for the existing CERN machine will provide as much as 60 Gev in the center of mass system by colliding two beams going in opposite directions, instead of about 20 Gev which will be available in proton-proton collisions at NAL. Hence negative results in the particle searches may only prove the need to experiment at still higher energies.

In addition to the search for new particles, which will constitute about one-fourth of the initial experiments, a variety of other fundamental experiments will be done. These include studies of particle production which determine the flux of particles from a target at various angles and momenta. The object is to extend, to the higher energies, the spectrum of particles produced in collisions between particular incident beams and target materials. Experiments measuring the total cross sections or interaction probabilities will involve more quantitative studies of secondary beams before and after the particles strike a target. When graphs of cross sections of the particles are plotted against energy, they will provide a reference against which new theories can be tested.

Besides particle production and total cross-section measurements, the initial list also includes some dynamic interaction experiments involving elastic and inelastic scattering. All three types of experiments will be done at NAL for strong, weak, and electromagnetic interactions, but not, however, with equal emphasis. More than half of the initial experiments will take place in the meson (strong interaction) area, and electromagnetic interaction studies will initially be confined to searches for magnetic monopoles and heavy photons. Much of the work will essentially be the extension to higher energies of the kinds of measurements obtained with accelerators available now, although the physicists clearly hope to find new and unusual phenomena.

The early starting date and higher energies of the NAL synchrotron testify to the unusual success of the design and engineering effort, especially in view of the fact that the project has been receiving its funds more slowly than expected. The NAL administrative staff also has an admirable record in its nonscientific activities, such as its aggressive minority hiring and training programs, its architectural innovations, its pollution control and water resource planning, and its concern about economic and social impact on the surrounding communities. It seems clear, however, that this machine is unlikely to resolve all scientific questions about fundamental particles and forces. The future of high energy physics will continue to depend on new accelerators, whose cost and size have risen roughly in proportion to the energy of the accelerated particles. The Batavia accelerator will be an important step toward the unknown, but the step after that may well prove too expensive for any single country to undertake.

—Allen L. Hammond