**Phase diagram** of nuclear matter as a function of temperature and net baryon density indicates regions of extreme conditions in which one hopes to study nuclear matter with an ultrarelativistic heavy-ion collider. Nuclear fragments emerging from such collisions will briefly have baryon densities an order of magnitude higher than normal—the "nuclear fragmentation region"—simulating the state of matter inside neutron stars and supernovae. In the "central region" of low center-of-mass momenta, the departing fragments will have left behind a high-temperature excited vacuum state of near-zero net baryon density—approximating the first moments of the universe. Nuclear matter in both regions is expected to be a plasma of unconfined quarks and gluons—too hot or too dense for ordinary hadrons. Quantum chromodynamics predicts that these quark–gluon plasma regions will be separated from ordinary nuclear matter by a phase-transition region, where both the chiral-symmetry-breaking transition and the deconfinement transition occur. At subnormal temperature and density the normal "liquid" state exists in equilibrium with a gas of nucleons. Figure 1

# Major facilities for nuclear physics

**Proposed machines such as a multi-GeV electron accelerator and an ultrarelativistic heavy-ion collider promise to open new frontiers for the study of nuclei as unique many-body systems.**

Gordon Baym

Nuclear physics is now entering one of the most challenging and interesting periods in the half century since the discovery of the neutron. With the simple picture of the nucleus in terms of the single-nucleon shell model well understood, nuclear physicists are turning to focus on nuclei as finite, saturating, many-body systems. The dominant theme promises to be the rich physics generated by the extensive array of nuclear degrees of freedom—from pure nucleonic states, as in the shell model, to mesonic and excited hadronic states, through to quark–gluon degrees of freedom.

▶ The concerns of nuclear physics go beyond simply discovering the fundamental forces in nuclei. Even when dealing with reasonably tractable forces, as in electrodynamics, one cannot necessarily predict the range of physical phenomena in a system from the forces. Superconductivity, for example, would not have emerged simply from our theoretical understanding of the underlying electromagnetic interactions in metals. Discovering the variety of *collective* effects produced by many interacting degrees of freedom is a concern that nuclear physics shares with condensed-matter physics. Experience with other quantum many-body systems indicates that opportunities abound for uncovering new and subtle physical phenomena in nuclei.

Carrying out the program of nuclear physics in the coming years will require several new major accelerators, as well as smaller ones, using different yet complementary probes: electrons and other leptons, light hadrons and heavy ions. The long-range plan of the nuclear physics community, as formulated by the DOE–NSF Nuclear Science Advisory Committee,[1] calls, as first priority, for the construction of a 4-GeV, high-intensity, high-duty-factor electron accelerator. Such a machine—the 4-GeV Continuous Electron Beam Accelerator Facility—is currently being developed by the Southeastern Universities Research Association, to be sited at Newport News, Virginia (PHYSICS TODAY, September 1982, page 18; September 1984, page 55).

In addition, recognizing a qualitatively new scientific opportunity, the NSAC plan calls for construction of an ultrarelativistic heavy-ion collider. Figure 1 indicates the extraordinary range of conditions one hopes to explore with such a machine. In response, Brookhaven is proposing to build a 100 GeV-on-100 GeV (per nucleon) heavy-ion collider in the vacant 4-km-long Colliding Beam Accelerator tunnel (figure 2). Lower-energy colliders are also on the drawing boards at the Lawrence Berkeley and Oak Ridge National Laboratories.

While the long-range plan sees a major light-hadron facility in the United States further in the future, high-intensity proton accelerators, or "kaon factories," are being planned by Los Alamos (LAMPF II), as well as by TRIUMF in Vancouver and SIN in Switzerland; Brookhaven is also planning to increase the intensity of the AGS proton synchrotron.

## Scientific goals

Let us begin by understanding in more detail the scientific goals of the research to be carried out at the new major facilities endorsed by NSAC: the high-duty-factor electron accelerator and the ultrarelativistic heavy-ion collider. We will then discuss the proposed facilities themselves.

Historically, the nucleus has been viewed as a system of neutrons and protons, interacting through meson exchange (one-pion exchange, for ex-

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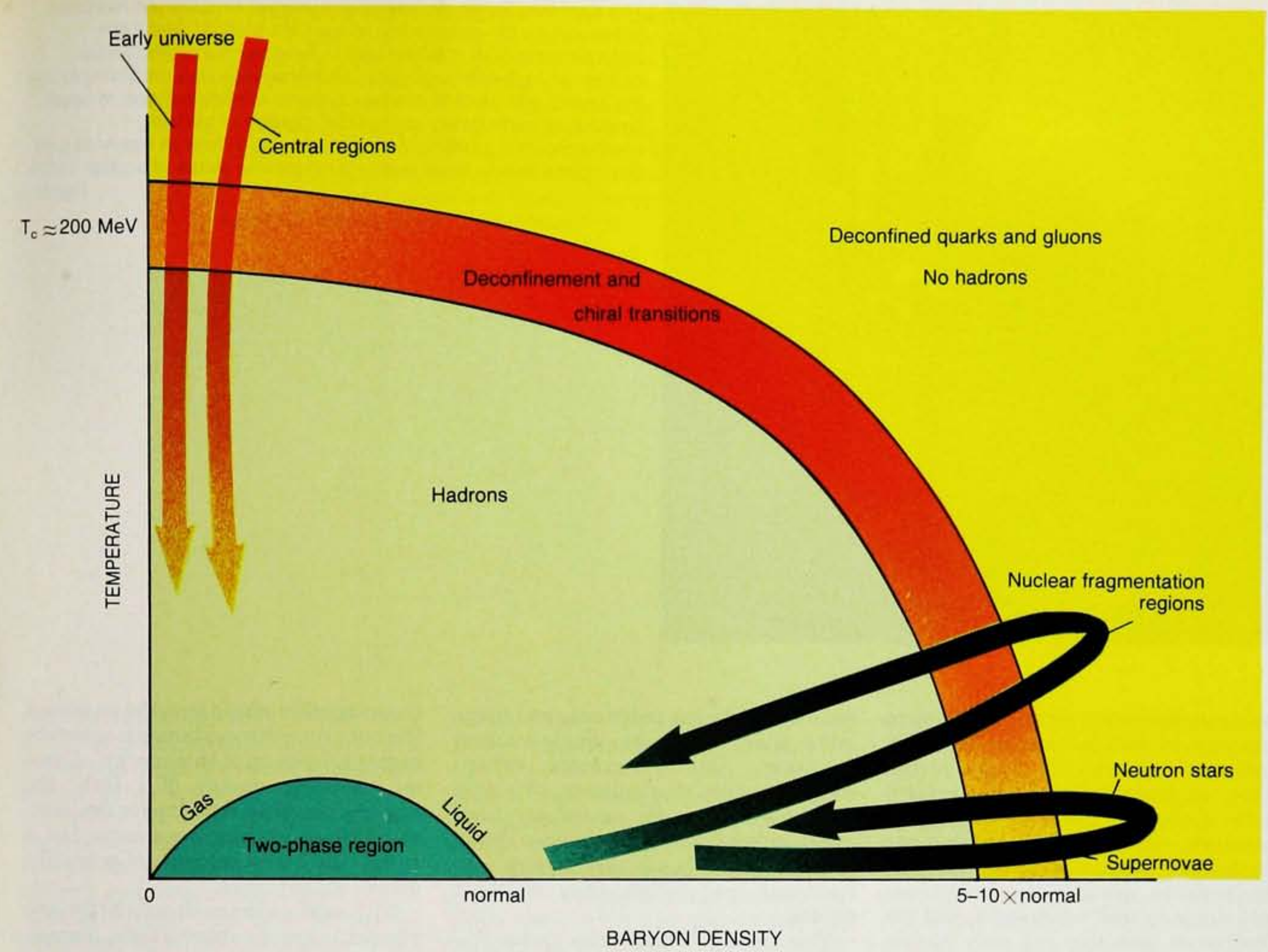



ample, when the nucleons are well separated). The quark model tells us, however, that all hadrons are composed of quarks: nucleons and other baryons of three quarks, and mesons of quark–antiquark pairs. The strong force, as described by quantum chromodynamics, ultimately arises from exchange of colored gluons. The quark–gluon picture not only deepens the hadronic description of nuclei, but raises as well the exciting prospect of understanding explicitly quark and gluon degrees of freedom in the nucleus.

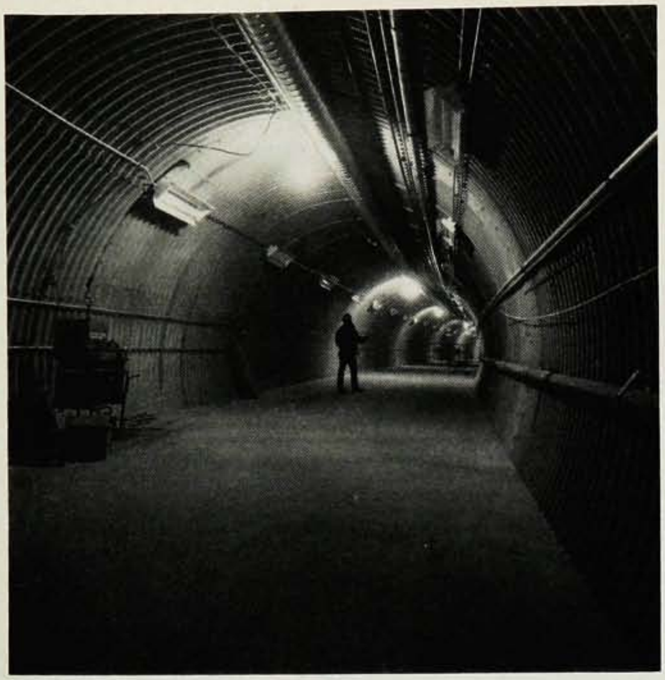
As in other strongly interacting systems, the effective internal degrees of freedom that describe the nucleus depend on the spatial scale on which one looks, or, equivalently, on the energy of the probing beam. The nuclear shell model describes phenomena on scales above about 1 fermi in terms of individual orbiting (point) nucleons and their collective motion in a potential well generated self-consistently by the forces between them. As one looks on finer spatial scales with more energetic probes, the underlying extended structure of the nucleon begins to play a role. At energies above a few hundred MeV, further "hadronic" degrees of freedom—mesonic excitations and resonant excited states of the individual nucleons, for example—must be taken into account. The picture of nuclear forces in terms of meson exchanges begins to break down as the extended nucleons begin to overlap. The significant progress already made in understanding nuclei at this level—for example, the discovery of meson-exchange currents, the electromagnetic currents carried by the mesonic degrees of freedom—is just beginning to spell out the full effects of the hadronic degrees of freedom and their modification by the nuclear medium.

On still finer scales, smaller than the size of the nucleon itself, corresponding to energies in the GeV range, the full quark structure of the nuclear constituents comes into play. A whole new picture emerges of the nucleus as a large collective system of quarks and gluons. One fascinating problem on this level is the exploration of the transition from hadronic degrees of freedom, which describe low-energy, low-momentum nuclear physics, to quark–gluon degrees of freedom, which govern phenomena at high energy and momenta.

A first hint of new behavior on this level, the "EMC effect," has come from measurements at CERN[2] by the European Muon Collaboration, and at the Stanford Linear Accelerator Center,[3] of the difference between the momentum distributions of quarks in nuclei and those within free nucleons. As figure 3 shows, these data indicate a shift of the momentum distribution of quarks in nuclei to lower momenta. This phenomenon has been variously interpreted in terms of overlap between quarks of neighboring nucleons, or as a size increase of nucleons when they are in nuclei. A full understanding of the effect, however, must await more data and more complete understanding of the structure of the nucleon itself. The very fundamental problem of the transition from nucleon–meson degrees of freedom to quantum chromodynamics is really that of understanding the mechanism by which quarks and gluons are confined in hadrons. Nuclei function as a unique laboratory for studying these issues, because by varying the energy and the nuclei involved in a particular experiment, one can modify the environment producing confinement.

## Electromagnetic probes

To search for manifestations of new nuclear degrees of freedom requires, on the one hand, high-precision experi-



**The Colliding Beam Accelerator tunnel** at Brookhaven has been left vacant by the cancellation of the CBA project. The 4-km-circumference CBA machine was to have been a proton–proton collider for high-energy physics. Brookhaven is now proposing to use the tunnel, with all of its auxiliary systems already in place, to house an ultrarelativistic heavy-ion collider, capable of colliding countercirculating 100-GeV/nucleon beams of ions as heavy as gold. One hopes thus to study quark–gluon plasma states of nuclear matter. Figure 2

ments to determine properties of wave functions of nuclear states relatively close to the ground state, and on the other, explorations of highly excited states of nuclear matter. For studies of structure, electromagnetic probes are particularly clean and powerful. The fundamental interaction of electrons with nuclei is well understood, and the electron is sensitive not only to the nuclear charge density but also to convection currents and magnetization density. Indeed, electron scattering, with its low-emittance beams, its high-energy-resolution detectors, and the kinematic versatility allowed by independent variation of the energy and momentum transfer, has provided our most precise knowledge of nuclear and nucleon structure. Examples include distributions of ground-state charge, magnetization, and transition densities; structure of single-particle, single-hole, and collective states; and evidence for meson-exchange currents.

Light-hadron beams of protons, antiprotons, pions and kaons can probe further aspects of structure, including features inaccessible to electrons, such as the baryon density distributions and gluon content. But hadron-beam data are complicated by the fact that the basic hadronic interaction is less well understood than the electromagnetic interaction.

The information that electron scattering provides about nuclear states and dynamics is remarkably increased if one is able to detect final-state products of the nucleus in coincidence with the scattered electron, thus isolating particular channels. For example, one can probe short-range nucleon correlations in the nucleus by two-nucleon knockout reactions, and deep-lying hole states by single-nucleon knockout. But coincidence experiments require the isolation of single events in time. An acceptably high event rate in such experiments therefore requires a beam that arrives continuously (cw) rather than in short pulses.

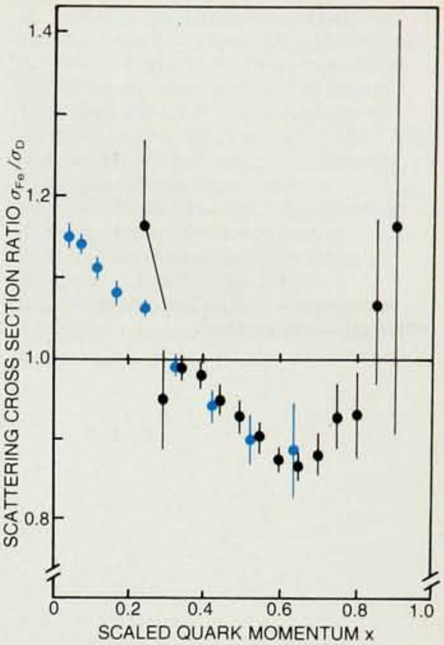
This need for high duty factor, together with the advent of the relevant accelerator technology, has strongly motivated the nuclear community in the past decade to give its top priority to the construction of a high-intensity, high-duty-factor electron facility. Present electron-beam facilities, by contrast, have duty factors on the order of 1% or less. Although low-duty-factor facilities will be able to carry out a range of important noncoincidence experiments such as deep inelastic scattering from nuclei, before a multi-GeV cw facility becomes available, they cannot begin to provide the detailed information on nuclear structure at the subnucleon scale that will be available from a cw, high-intensity, multi-GeV electron accelerator.

The optimal choice of energy for such an electron machine has been the subject of considerable debate. An energy of 2 GeV, corresponding to a spatial resolution about 0.1–0.2 fm, represents a minimum requirement for a substantial program to explore hadronic degrees of freedom in nuclei by coincidence experiments. Studies of few-nucleon systems and hypernuclei can also be undertaken at 2 GeV, as can significant tests of fundamental symmetries—for example, parity nonconservation. Furthermore, because the spatial scales at 2 GeV are smaller than the intrinsic nucleon size, the physics of the quantum-chromodynamic interface begins to open up at this energy. Above an excitation energy of 1 GeV, the nucleon response is no longer dominated by sharp nucleon resonances, but is rather the broad response of point-like quark constituents.

Although no sharp threshold for new physics is known above 2 GeV, increasing the beam energy has the important practical advantage of increasing the kinematic flexibility of the machine, and thus both the rate at which experiments can be carried out and the information that they provide. The very small cross sections of electromagnetic processes increase strongly with decreasing scattering angle. Higher energies, by permitting one to produce a given momentum transfer at a smaller electron scattering angle and hence with a higher cross section, make possible previously unfeasible experiments. Smaller scattering angles also permit cleaner separation of the response of the system to longitudinal and transverse electromagnetic probes. Generally, higher energy allows one to probe smaller spatial scales and higher energy losses. These arguments have weighed strongly in the nuclear community's preference for 4 GeV rather than a lower-energy cw electron accelerator (see PHYSICS TODAY, September 1982, page 20).

Quantum chromodynamics has the remarkable property of becoming "asymptotically free" at small distance scales. As the quarks come closer to one another their interactions weaken; at sufficiently small distance they can be treated perturbatively. It is important to realize, however, that in the

**The "EMC effect,"** seen here in deep inelastic scattering of high-energy muons (colored data points from the European Muon Collaboration) and electrons (black data points from the Rochester–MIT–SLAC collaboration) off deuterons and iron nuclei. It exhibits the unexpected shift of the quark momentum distribution to lower momenta in large nuclei as compared with deuterons. The ratio of scattering cross sections is plotted against the scaling variable $x$, a function of the observed energy and momentum transfer of the scattered lepton that measures the fraction of the nucleon's momentum carried by the quark scatterer. Figure 3




regimes reachable with 4-GeV electrons, QCD interactions are generally strong and nonperturbative. Studies of production processes for particular final states in this "QCD interface" regime will not reach "asymptopia." Rather, they will focus on the more difficult and interesting region of the transition from hadronic to quark–gluon degrees of freedom and the mechanism of quark confinement. That this regime involves strong interactions does not imply, however, that it is intractable. We know from other systems of fermions such as liquid $He^3$ and, indeed, from atomic nuclei, that strong-interaction regimes often display interesting quasiparticle structures and other simplifying collective effects.

To exploit the simplicity of asymptotic QCD requires substantially higher energies—tens to hundreds of GeV. Studies in this regime at high-energy facilities, such as the 20-GeV electron beam at SLAC and the 800-GeV muon beam soon to be completed at Fermilab, are an essential component of a fully structured program of electromagnetic research on nuclei.

## Ultrarelativistic heavy-ion collisions

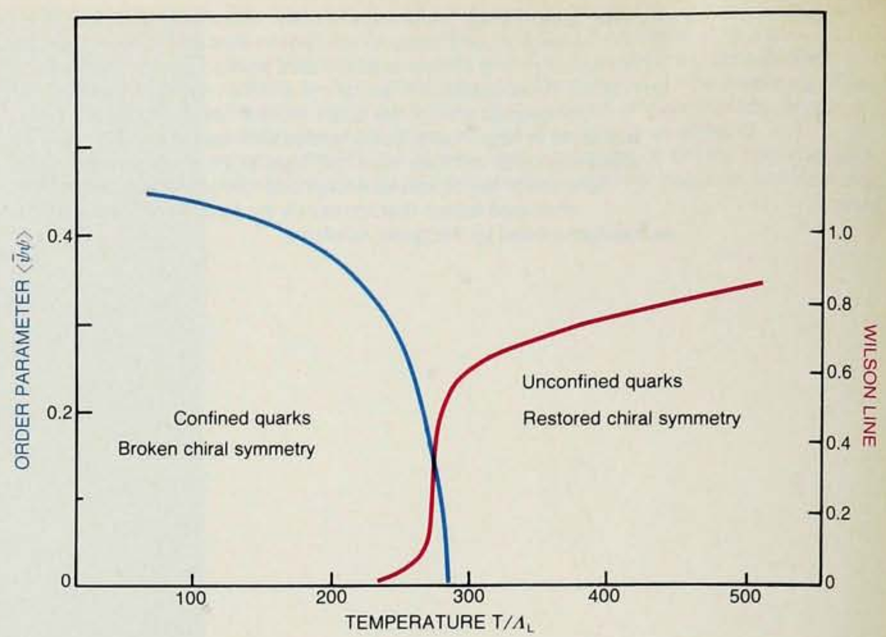
A rather different approach to the physics associated with new degrees of freedom, quark confinement and the transition to QCD is provided by ultrarelativistic heavy-ion collisions, for example, collisions between uranium beams as energetic as 100 GeV/nucleon (in the center of mass frame!). Such collisions would explore highly excited states of nuclear matter, complementing studies near the ground state by electron and light-hadron probes. They present us with the unique opportunity to study hadronic matter in the entirely uncharted regions of high energy density and baryon density over large spatial distances. They further open the possibilities of producing aı entirely new state of matter—a "quark–gluon plasma," in which the quarks and gluons are not confined in individual hadrons—and exploring quark degrees of freedom and their interactions in highly excited states of matter, over distances on the order of the nuclear radius, inaccessible in single-hadron collisions.

The states of matter that can be explored in heavy-ion collisions are conveniently summarized in figure 1, the phase diagram of extended and equilibrated matter at high baryon-number density, $n_b$, and temperature, $T$. At low $n_b$ and $T$, matter consists of confined hadrons; the relevant degrees of freedom are baryonic and mesonic. As the energy density is raised, with increasing $T$ or $n_b$ or both, one begins to reach states in which the quarks and gluons become deconfined: A simple first picture of the deconfinement process is that, by depositing large energy densities over extended volumes of nuclear matter and thus creating enough hadronic excitation (by heating or compression), one causes the individual hadronic "bags" (the wells in which the quarks and gluons are confined) to fill space until they overlap completely and merge into a single bag over whose entire volume the quarks and gluons can roam.

The energy densities needed to produce deconfinement are an order of magnitude greater than the energy density (0.15 GeV/fm$^3$) of a nucleus in its ground state. Lattice gauge theory[4] estimates the deconfinement temperature (at zero net baryon density) to be about 200 MeV, corresponding to an energy density above 1 GeV/fm$^3$. The deconfinement density at $T=0$ is variously estimated to be 5 to 10 times normal nuclear-matter density. Achieving sufficient energy density to produce a quark–gluon plasma thus requires central heavy-ion collisions with energies well above 1 GeV per nucleon in the center of mass.

At the same time that heavy-ion collisions enable one to study quark confinement, they also permit studies of one of the fundamental and nearly exact symmetries of the strong interaction—chiral symmetry. Chiral symmetry, which arises from the underlying conservation of the vector current and partial conservation of the axial current, means in essence that overall phase rotations of the right-handed and left-handed spinning fermion states (independently of one another) do not change the physics (to a very good approximation for the strong interaction). It functions in hadronic matter analogously to rotational symmetry in a ferromagnet. For example, chiral symmetry is spontaneously broken in the hadronic phase in the same way as rotational symmetry in a ferromagnet. The pion, whose mass is relatively small compared with the nucleon, can be thought of as the low-lying excitation associated with this symmetry breaking—analogous to spin waves in a ferromagnet (long-wavelength oscillations of the magnetization direction). Furthermore, in the same way that the state of a ferromagnet is rotationally symmetric at high temperature, one

**The quark deconfinement transition** is predicted by lattice gauge theory to occur at the same temperature (at zero baryon density) as the chiral-symmetry-breaking phase transition. The order parameter $\langle\bar{\psi}\psi\rangle$, which measures the degree of chiral-symmetry-breaking, and the Wilson line, which measures the degree of deconfinement, are both calculated to go to zero at a temperature near 300, measured in units of the lattice QCD scaling parameter $\Lambda_L$. At higher temperature, quarks are unconfined and chiral symmetry restored. Figure 4




expects from the asymptotic freedom of QCD that the deconfined phase at high energy density should have a fully restored chiral symmetry. In fact, lattice-gauge-theory calculations[4] indicate that chiral symmetry becomes restored at the same point at which the matter becomes deconfined, and that both transitions are first order.

These lattice-gauge-theory predictions (for QCD with light quarks, SU(3) color and zero baryon density) are summarized in figure 4, which shows, as a function of the temperature, the order parameter $\langle\bar{\psi}\psi\rangle$, a measure of the degree of chiral-symmetry breaking; $\langle\bar{\psi}\psi\rangle$ is zero in the phase in which chiral symmetry is fully restored. The plot also shows the "Wilson line," which measures the degree of confinement. Effectively, this line is given by $e^{-E(R)/T}$, where $E(R)$ is the energy of a heavy test quark–antiquark pair separated to large distance $R$. In the confined phase, the Wilson line vanishes in the absence of light-quark pair creation, and is generally much smaller than in the deconfined phase, where it costs less energy to separate a pair of test quarks to infinity.

The deconfined regions of the phase diagram, and the deconfinement and chiral-symmetry transitions should, according to present lore, be reachable with heavy ions of energy above 30 GeV per nucleon in the center of mass. It is even possible that they may be reached to a limited extent by heavy-ion collisions of energy as low as a few GeV per nucleon in the center of mass. One requires *heavy* ions for sufficient energy to be deposited over a large volume, and to establish local thermal equilibrium within the collision volume.

At the low-energy end, colliding nuclei of 3 to 5 GeV per nucleon (equivalent to 10 to 30 GeV per nucleon with fixed targets) are estimated to have the greatest stopping power for nucleons. In a head-on collision in this range, the two nuclei nearly stop each other, generating a dense fireball; one might achieve energy densities of several $GeV/fm^3$, an order of magnitude beyond that of normal nuclei, with associated compression to baryon densities perhaps exceeding $1\ fm^{-3}$. A normal large nucleus has a baryon density of about $0.16\ fm^{-3}$. The temperature–density trajectory of the central matter in such a collision (labeled "nuclear fragmentation regions") is schematically indicated in figure 1. Fixed-target experiments in this range are planned for 1986 at the CERN Super Proton Synchroton complex with an $O^{16}$ beam, and at the Brookhaven AGS with projectiles as heavy as $S^{32}$. These experiments should serve as a first exploratory step. However, because the projectiles are so small, they should not necessarily be expected to yield qualitatively new physics.

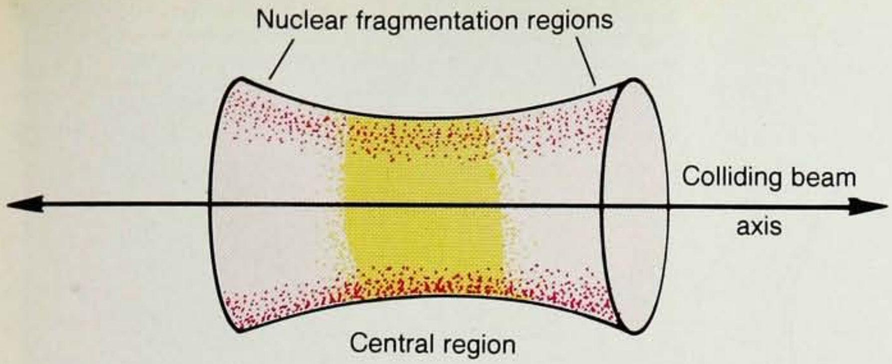
At the much higher energies envisioned for an ultrarelativistic heavy-ion collider (30 to 100 GeV per nucleon in the center of mass), effects of nuclear transparency set in, and two nuclei in a head-on collision pass through each other rather than "stopping." In doing so, they become highly excited and leave behind a very excited state of the vacuum—this is the "central region" of small longitudinal momentum in the center-of-mass frame. Figure 5 is a schematic view of the system after such a collision, showing the two very hot, compressed and fragmented nuclei leaving the collision site at high longitudinal velocity. These "fragmentation regions" of phase space contain the net baryon density of the original nuclei.

In the central "firetube," by contrast, the number of baryons is approximately equal to the number of anti-baryons. As shown by the trajectory labeled "central region" in figure 1, the matter in the central phase-space region of low center-of-mass momenta is created, through extensive excitation of quark–gluon degrees of freedom, at very high energy density but relatively low net baryon density. According to present estimates, the excited central region left behind by the departing fragmented nuclei comes into local thermal equilibrium as a quark–gluon plasma. The matter then cools in the post-collision expansion of the system, passing through the hadronization transition in which the quarks become confined, ultimately emerging as free-streaming ordinary hadrons, mostly pions.

Just as in lower-energy collisions, the two fragmentation regions are expected to explore regions of very high baryon density, probably crossing the transition into deconfined quark matter. Generally, higher-energy collisions are capable of exploring the phase diagram over a wider range of baryon densities and excitation energies.

## Astrophysical applications

In addition to their intrinsic interest for nuclear physics, ultrarelativistic heavy-ion collisions will have substantial astrophysical applications. Only through such collisions can we learn in the laboratory about matter under the extreme conditions in the cores of neutron stars and in the gravitational collapse of massive stars, and thus about the upper mass limit of neutron stars and the transition to black holes. X-ray satellite measurements of neu-




**Quark-gluon plasma.** $10^{-23}$ seconds after an ultrarelativistic head-on collision between heavy ions, one expects to see an expanding "firetube" of quark–gluon plasma, coaxial with the direction of the incident nuclei. The "central region" left behind near the collision point by the departing fragmented nuclei is very hot, with quarks and antiquarks in roughly equal numbers—essentially an excited vacuum. The firetube flairs out at larger longitudinal distances—the "fragmentation regions," where the departing fragmented nuclei form a different quark–gluon plasma, with net baryon densities an order of magnitude higher than normal. Figure 5

tron-star surfaces provide information that can be directly correlated with the properties of matter in the deep interiors. Figure 1 also indicates the extreme states of matter in astrophysical situations. The one case in which we are quite sure that a quark–gluon plasma existed was in the first microseconds after the big bang. The behavior of matter in the central phase-space region of ultrarelativistic heavy-ion collisions in the laboratory should closely mimic that in the early universe, including a replay of the primordial hadronization phase transition.

Extracting information about these as yet unexplored states of matter from such collisions is clearly a complex task. In particular, predicting detailed signals of deconfinement requires fuller understanding of the physics of strongly interacting quark–gluon plasmas. It is possible that we will not gain such understanding before the experiments are actually carried out. Many different experimental approaches are being considered.[5,6]

The first class of approaches involves studying the global parameters of events: The spectra of the emitted particles would measure the entropy density of final states, and their dependence on beam energy and mass number would serve as an indicator of possible phase transitions; with the added information from interferometry of the emerging particles such as pions, one would be able to measure source temperatures, densities and sizes. Multiparticle correlations in longitudinal phase space would indicate energy flow, hydrodynamic behavior and collective modes. A second class of experimental approaches involves direct probes of the interior of the collision through detection of direct lepton-pair and photon production, involving several different emission mechanisms.

Hadron production can also give information about the unusual conditions expected in an ultrarelativistic heavy-ion collisions. Increased production of strange antiquarks for example, may signal the presence of a quark–gluon plasma. Head-on collisions between hadrons at high energy occasionally result in a pair of "jets"—well-collimated sprays of hadrons—going off at high momentum in opposite directions transverse to the beam. Such jet pairs produced in heavy-ion collisions might serve as powerful probes of nuclear matter *in extremis* when one of the jets passes through the collision volume.

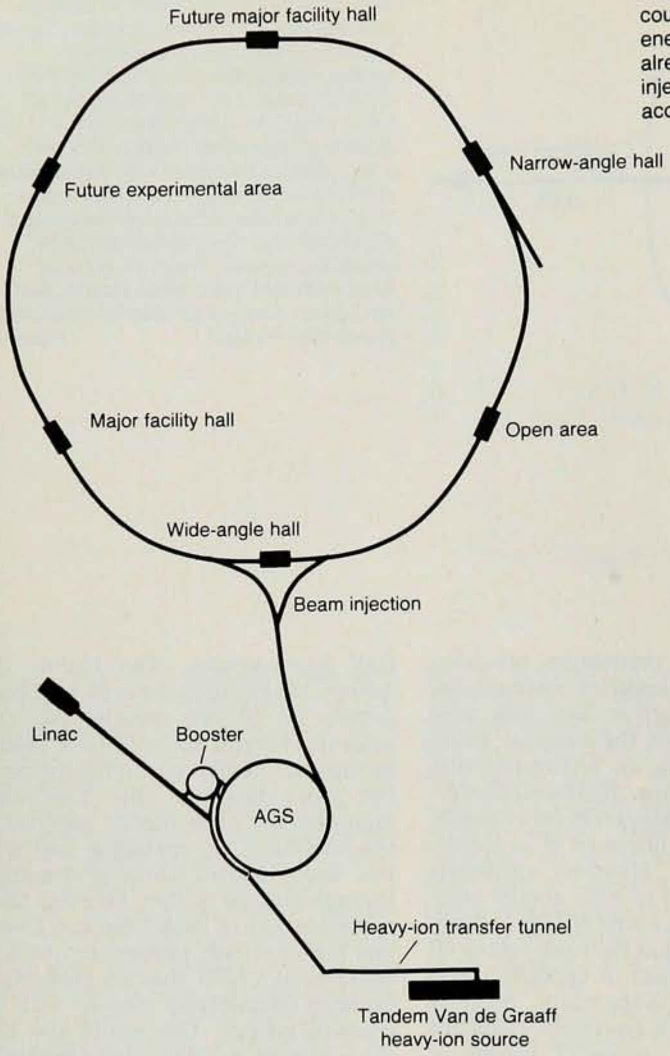
Furthermore, one can speculate on the unusual objects that may possibly be made as a quark–gluon plasma expands and hadronizes: multiquark states, hadrons involving heavy quarks, extended metastable quark droplets of large strangeness and fractionally charged particles. The chiral-symmetry-breaking transition might even produce multibaryon states of unusual chiral topology, as one imagines magnetic monopoles might have been created in phase transitions in the early universe. We must, of course, also be prepared for Nature to surprise us in the way it reveals the physics of this unexplored regime, as it did in first presenting neutron stars to us in the form of pulsars.

## The new accelerators

Several factors enter into the choice of general parameters of an ultrarelativistic heavy-ion collider. The central phase-space region in a heavy-ion collision, where the net baryon density is small, begins to open up above about 30 GeV per nucleon. The higher the energy, the larger is the ratio of energy density to baryon density one can achieve; energies above 50 GeV should be capable of reaching a large region of the phase diagram. One interesting argument for even higher energies is the possibility of producing hadronic jets and studying their propagation through nuclear matter. One sees from a comparison of data from the lower- and higher-energy elementary-particle colliders at CERN that jet production becomes considerably cleaner with increasing energy. One would also like the heavy-ion collider to have sufficient dynamic range to be tunable in energy down to the range of the fixed-target experiments at Brookhaven and CERN.

It is important that a collider be able to accelerate beams from the lightest ions (protons and alphas) all the way up to very heavy ions, and that it allow for collisions of species of unequal mass. One can then carry out systematic studies, increasing both mass number and energy, to look for onsets of structure indicating possible phase transitions and other phenomena. In addition to soft mass-number dependences, one may in fact discover strong mass-number dependences associated with the infrared behavior of QCD. The ability to vary the nuclear size over as large a range as possible provides a good handle on such effects.

Head-on collisions of heavy ions will produce on the order of a thousand particles per event. Such wild profusions have already been observed in cosmic-ray collisions by the Japanese–American Cooperation Emulsion Experiment.[5] A heavy-ion collider thus does not require high luminosity. A luminosity (defined as event rate per




**The ultrarelativistic heavy-ion collider** Brookhaven proposes to build in the vacant CBA tunnel. Beams of ions as heavy as gold would countercirculate around the 4-km-circumference machine with energies up to 100 GeV per nucleon. Three experimental halls already exist, and the design allows for three more. The source–injector complex would use the existing Van de Graaff and AGS accelerators. Figure 6

unit scattering cross section) of $10^{25}$ events per $cm^2$ per sec, which is low by high-energy-physics standards, should yield about one interesting event per second, corresponding to some $10^{10}$ particles per year (plus a factor of 10 more from glancing collisions). Higher luminosity is desirable, however, for interferometry experiments and searches for rare processes.

Brookhaven has recently submitted a proposal to DOE for the construction of a Relativistic Heavy Ion Collider, which would meet these general specifications. Because of the important role this proposed machine is playing in consideration of colliders for heavy ions, and to develop a feeling for the scale of projects that nuclear physics is embarking upon, let us look briefly at its parameters. The main ring, with common low-field superconducting magnets for the two counter-circulating beams, is designed to fit into the 4-km long tunnel left vacant when the Colliding Beam Accelerator project, a proton–proton collider (formerly called Isabelle) intended for high-energy physics, was terminated.

The Brookhaven heavy-ion collider machine would be capable of accelerating ions from very light elements through to gold, the latter from energies of about 10 to 100 GeV per nucleon. For the heaviest collision partners, Au on Au, the luminosity would range with increasing beam energy from about $10^{25}$ to $10^{27}$ events per $cm^2$ per sec. Beams of different masses would have the same maximum energy per proton, so that the maximum energy per nucleon increases with decreasing mass number, to a maximum of 250 GeV for a proton beam. (The proton capability is necessary for comparing ion–ion with nucleon–ion collisions.)

As figure 6 shows, the Brookhaven collider facility would have a minimum of three experimental areas (already built)—with the eventual possibility of six, including an internal fixed target. These areas would house a large-solid-angle general spectrometer as well as specialized detectors for such processes as jet and dilepton production. The beam would begin at the present Tandem Van de Graaff source (figure 7), and it would be carried along a 2000-ft transfer line to the AGS proton synchrotron. This transfer line, currently under construction, will allow fixed-target experiments in the AGS in 1986.

Prior to injection into the AGS ring, the ions would be fed through a new booster synchrotron—on which Brookhaven hopes to begin construction in a year's time—there to be accelerated to about 2 GeV per nucleon. (Aside from its role in heavy-ion acceleration, the booster will serve to expand the AGS program of kaon-factory physics by increasing the AGS proton intensity.) Then, after a final complete stripping, the ions would enter the AGS to be accelerated to the maximum AGS energy (11 GeV per nucleon for Au), and then injected into the main collider ring.

According to the Brookhaven proposal, a first estimate of the price of outfitting the CBA tunnel with the ion accelerator is about $135 million, plus the cost of the experimental detectors,

**The Tandem Van de Graaff** accelerator at Brookhaven is being upgraded in support of the Laboratory's relativistic-heavy-ion project for the Alternating Gradient Synchrotron. Looking along the high-voltage support column inside the Van de Graaff's (horizontal) pressure vessel, one sees the "portico intershield" being installed—eight radial panel structures that will provide higher voltage in normal operation and increased reliability at the 15-megavolt level necessary for injection of ions into the AGS. A tunnel to transfer ions from the Van de Graaff to the AGS is now under construction. The system would eventually serve as the source and injector for the ultrarelativistic heavy-ion collider Brookhaven proposes to build in the vacant CBA tunnel. Figure 7

perhaps another $50 million. With a completion time of five years, the first ultrarelativistic collisions could take place there in the early 1990s.

Let us take a similar look at the 4-GeV high-intensity, high-duty-factor electron machine being developed by SURA. We have already recalled the arguments for continuous-beam operation to allow coincidence experiments, as well as the arguments for the choice of energy. It is also crucial, if the machine is to function as a national multiuser facility, that it have a high beam intensity, on the order of several hundred microamperes cw, to permit operation with multiple extracted beams.

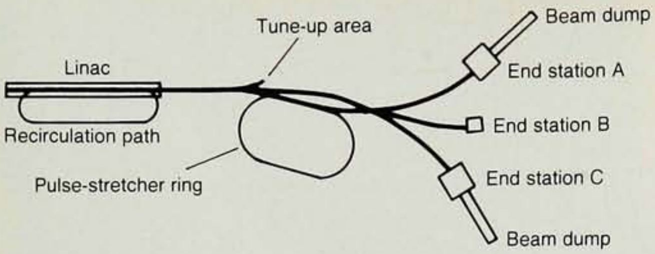
This CEBAF machine, shown schematically in figure 8, is conceived as a pulsed linac with a pulse stretcher ring, a design based primarily upon existing technology, with the capacity to be upgraded to higher energies. The linac, containing accelerator elements similar to those at the SLAC linac at Stanford, is being designed to produce 1.2-microsecond electron pulses of energy from 0.5 to 4.0 GeV, with a 1-kHz repetition rate, at a peak output current of 200 milliamperes. To produce electrons with energy below 2 GeV will require only a single pass through the linac; but to reach the full 4 GeV the beam must be recirculated once, by means of a recirculation pathway on the side of the linac.

After acceleration by one or two passes through the linac, the beam pulse is injected into the pulse-stretcher ring, 360 m in circumference, whose purpose is to stretch out a thousandfold the time over which the pulse is delivered to the experimental target. The beam pulse is then extracted from the stretcher ring over a millisecond to produce a smooth beam with an average current of 240 microamperes and energy resolution better than one part in $10^3$. Similar pulse-stretcher rings are being developed at several electron facilities abroad, particularly in Bonn and Sendai. The beam from the pulse-stretcher ring is fed into a switchyard, which then splits it to supply three experimental stations housing a variety of specialized spectrometers. Two of the endstations (A and C) can be fed directly from the linac. The design also calls for a photon-beam generation and "tagging" facility (where each photon's energy is known from the recoil of the electron that produced it) at endstation B, which would allow a variety of precision photonuclear studies.

The cost of the CEBAF facility, still in a state of flux, is a figure on the order of $185 million (1984 dollars) corresponding to a final cost (in actual dollars) of about $225 million, including experimental equipment. Construction time is also about four or five years, which, with a smooth flow of funding, would allow the first experiments to begin in 1990.

### Planning for the future

Having discussed the physics and the technical details of the proposed major machines for nuclear physics, let us step back and look at the process of deciding on priorities and plans for the future. The strong commitment of the nuclear community to construction of a




**The Continuous Electron Beam** Accelerator Facility proposed by the Southeastern Universities Research Association for a site at Newport News, Virginia, would provide high-intensity, high-duty-factory, 4-GeV electron beams to three experimental end stations. Short pulses of electrons, recirculated once through the 2-GeV linac, would be injected at 4 GeV into the stretcher ring, which is designed to expand the pulses in time to provide almost continuous beams. This stretching out of the electron beam's time structure is crucial for coincidence experiments. Figure 8

high-intensity, high-duty-factor electron accelerator has a long history, beginning with the National Academy of Sciences 1976 Friedlander report (prior to the establishment of NSAC) and the NSAC 1979 Long Range Plan, through to the 1982 Barnes Report, the 1983 Bromley Report, the present NSAC Long Range Plan[1] and the recent Vogt Committee Report on a multi-GeV electron accelerator (see PHYSICS TODAY, November 1984, page 59). Although legitimate scientific questions (raised in Congress, and elsewhere) have caused nuclear physicists to sharpen their perspective on the physics studies at such a machine, the commitment of the community (contrary to impressions portrayed in the popular literature) to the absolute importance of precision electron studies in opening up a richer and deeper picture of the nucleus has never been in question.

The wide range of phenomena possible in the nuclear many-body system requires exploring nuclei with a corresponding diversity of probes. One of the principal goals of the 1983 NSAC Long Range Plan was to establish priorities among possible new facilities. In view of the unusual scientific potential of ultrarelativistic heavy ions, and given the fact that the electron machine had already been endorsed, the plan concluded that "the United States should proceed with the planning for the construction of this relativistic heavy-ion collider facility expeditiously, and we see it as the highest priority new scientific opportunity within the purview of our science."

One consequence of the need to set priorities has been the inability to call at the same time for a major light-hadron facility, a complex based on a high-intensity proton accelerator. But the importance of probes such as protons and secondary beams of antiprotons and mesons, as well as neutrinos, should not be understated. They are certainly needed to study the full range of physics associated with all hadronic degrees of freedom and explore the interface with QCD within the nucleus. Furthermore, kaon and neutrino beams can be used to carry out a wide variety of new tests of the "minimal standard model" of strong and electroweak interactions.

Los Alamos is currently designing such a light-hadron facility—LAMPF II—in which the present LAMPF 800-MeV linac would inject protons into a 6-GeV booster ring; the extracted proton beam would then be split to feed a 45-GeV main synchrotron ring, and simultaneously to generate a neutrino beam of GeV energy. In addition to generating secondary kaon, pion and antiproton beams, the primary proton beam would supply two stations for proton experiments.

Nuclear physics, in moving toward large-scale facilities, is embarking on a new and ambitious course, which high-energy physics has been following for quite a while now. However, the diversity and health of the field requires that these facilities not be the only places where nuclei can be studied. Small accelerators and nonaccelerator facilities must remain an essential component of nuclear research in the future. The Vogt Committee was careful to point out the need in electromagnetic research for a structured program, including, in addition to the 4-GeV facility, more vigorous use of high-energy-physics facilities, and upgrades that would provide continuous-beam capabilities up to about 1 GeV at existing electromagnetic facilities. More generally, it is vital that the move towards large facilities not cause basic research at universities, the ultimate source of talent, to be neglected.

This new course will beneficially transform nuclear physics research into a far more international undertaking than it now is. With their unique capabilities, the new machines will represent worldwide scientific resources; not only will they attract international user groups, but they will also present the opportunity for international cooperation in their implementation and instrumentation.

The proposed facilities grow out of a unified concern with understanding the full range of degrees of freedom and physical phenomena in nuclei. Although quite different in structure and conception, they will make possible complementary advances on the same fundamental frontier. But they will function independently. This means, in particular, that funding and construction scenarios for the new machines can and should be decoupled.

The present annual budget for basic research in nuclear physics in the United States is $225 million. The total cost of the new electron and heavy-ion facilities, spread over the next six or seven years, thus represents 20–25% of the total support for basic nuclear physics. The argument for these major nuclear-physics facilities is not immediately practical application (beyond development of accelerator and related technologies). One should, however, remember that a surprisingly large part of modern medical technique—from radiotherapy and nuclear chemistry to nmr and gamma-ray tomography—has grown, over rather long times, out of basic research in nuclear physics. Still, the principal justification is the opportunity to discover the fascinating and challenging new science that nuclei present. The new facilities should give us in the coming years every bit as striking and far-reaching a picture of the nuclear many-body system as we are beginning to have of more familiar condensed-matter systems.

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