RECENT ACCOMPLISHMENTS

Revealing the internal structure of nucleons—A new generation of experiments, coupled with more sophisticated theoretical and computational techniques, has challenged earlier perceptions of nucleon structure. The importance of gluons has been emphasized by their rapidly growing density as the proton is probed with higher resolving power, and by the fact that quark spins alone account for only a fraction of the nucleon's overall spin. A sizable measured imbalance between antiquarks of different types suggests that pi mesons play as important a role inside nucleons as they do in theories of nuclear forces. A new high-resolution spatial map of the proton points to an unexpected depletion of charge near its center, not yet explained by current models. Surprisingly, the traditional description of nuclear forces continues to account well for the charge distribution of the deuteron, even at subfemtometer distances where the internal structures of the neutron and proton overlap strongly.

- Development of QCD-based models which are able to calculate experimental observables. Examples include effective field theories and models that invoke symmetries of QCD, such as chiral symmetry. Substantial progress is being made by use of large-scale computers, which perform detailed QCD calculations of nucleon properties using a discretized space-time lattice. These "lattice QCD" calculations have great potential to usher in a new era in understanding the fundamental structure of the proton and neutron.
- Novel consequences of confinement are predicted at relatively low energies, including new forms of matter known as "hybrids," in which the gluonic degrees of freedom are excited in the presence of the quarks.
- Studies of proton and neutron structure using beams of leptons (i.e., electrons, muons, or neutrinos) or photons over a broad range of energies. Such experiments also provide especially sensitive ways of distinguishing the different "flavors" of quark, notably the up and down quarks that help to give protons and neutrons their separate identities. At low momentum transfers, static properties of the proton and neutron, such as their shape, size, and polarizability, are determined and compared with QCD-inspired models and lattice calculations. At high momentum transfers, the spatial, spin, and flavor structure of the proton and neutron are probed by scattering from the elementary quark and gluon constituents.

RECENT ACCOMPLISHMENTS (cont.)

Challenging traditional descriptions of the atomic nucleus—Exploration of the unknown regions of the nuclear landscape, toward the limits of nuclear existence, has begun. Studies of exotic nuclei point to drastic alterations of the nuclear shell model, a hallmark of our understanding for half a century. In very heavy nuclei, observations that they can sustain rapid rotation demonstrate unexpected stability against disruptive centrifugal forces and confirm that the path to "superheavy elements" goes through nuclei with deformed shapes. Striking evidence for phase transitional behavior in nuclei has emerged from observations of sudden changes with mass between spherical and deformed systems, and from evidence of changes between liquid and gaseous forms of nucleonic matter. Advances in theory, such as calculations with realistic forces in nuclei containing up to 10 nucleons—an achievement thought impossible just a few years ago—offer the promise of a unified description of the nucleus based on the theory of the strong interaction.

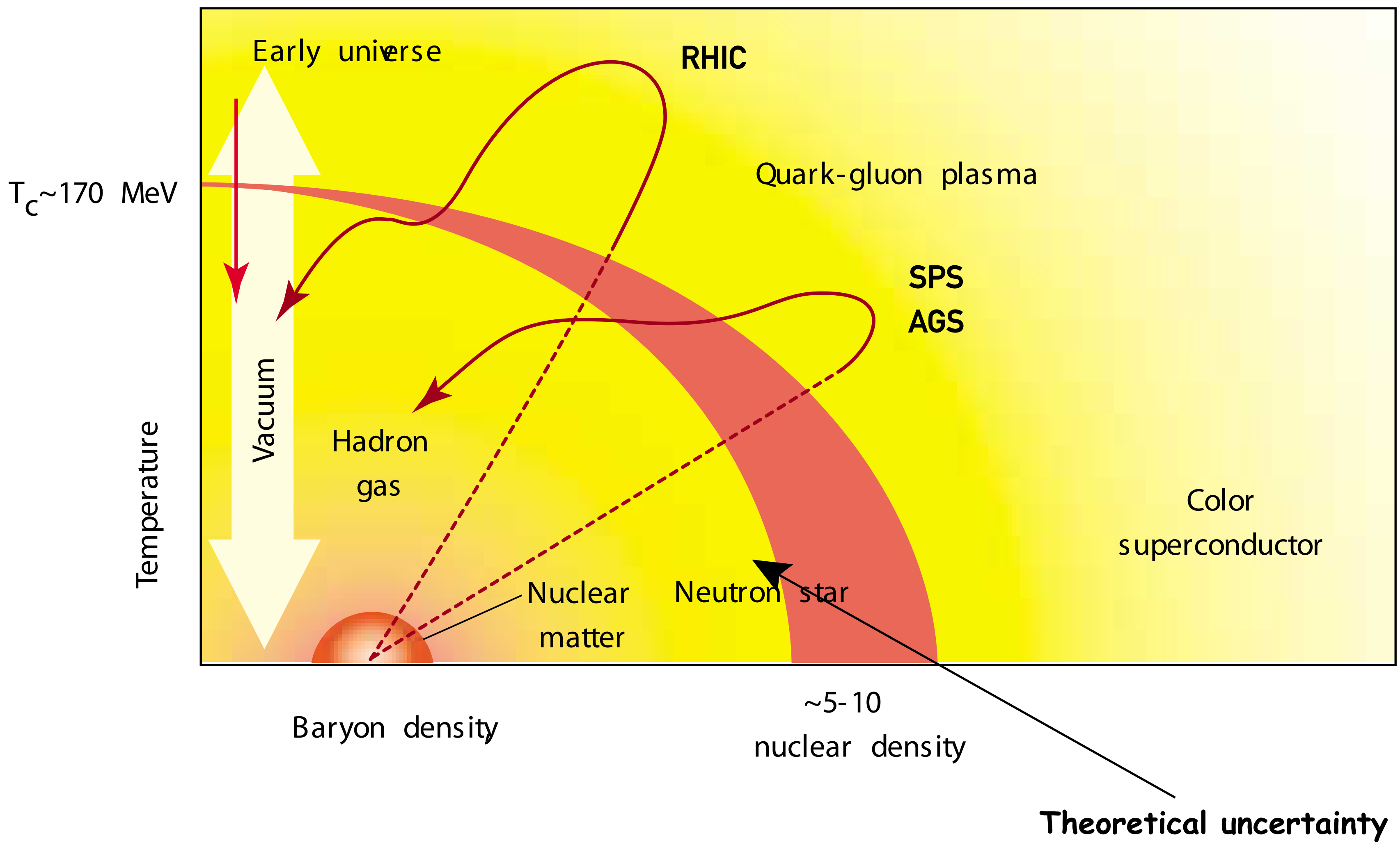
- Shell structure in exotic nuclei. Investigations of nuclear shell structure far from stability are fundamental to our understanding of nuclei and their synthesis within the cosmos. Recent landmark experiments include the observation of the doubly-magic unstable nuclei 48-Ni ($Z = 28$, $N= 20$) and 78-Ni ($Z = 28$, $N= 50$). In lighter neutron-rich nuclei, spectroscopic studies have demonstrated clear evidence for a reordering of nucleonic shells; for a weakening of the familiar shell closures around N= 8, 20, and 28. First signatures of a new form of pairing have been seen in nuclei with equal numbers of protons and neutrons, and a new decay mode, nonsequential two-proton radioactivity, has been discovered.
- Collective excitations. We gain insight into the properties of nuclei by establishing and studying their basic modes of excitation. Recent advances include the discovery of the first candidates for the new collective modes of chiral rotation and wobbling motion in triaxial nuclei.
- Synthesis, structure, and chemistry of the heaviest elements. The discovery and investigation of the heaviest nuclei test our understanding of which combinations of neutrons and protons can give rise to long-lived superheavy nuclei, and extends the periodic table, fundamental to all of chemistry. The first chemical studies of seaborgium ($Z = 106$), bohrium ($Z = 107$), and hassium ($Z = 108$); and the first in-beam gamma-ray spectroscopy of the trans-fermium nucleus nobelium ($Z = 102$).

RECENT ACCOMPLISHMENTS (cont.)

Searching for matter at extremely high energy density— The first year of RHIC data-taking has produced strongly self-interacting matter at energy densities more than 20 times that of atomic nuclei. Matter under such extreme conditions is believed to be in a new state—the quark-gluon plasma. The estimates of energy densities have come from measurements of the number and energies of produced particles. The observed “flow” of matter indicates that this energy is rapidly converted to nuclear matter that is under immense internal pressure. In addition, particles emitted at high momentum are considerably suppressed relative to the rate seen in proton-proton collisions—an effect occurring only if the interactions among the particles produced are very strong. These results provide a confirmation of the picture that originally motivated the field of ultrarelativistic nuclear collisions.

- Studies indicate that, in a nucleus-nucleus collision, the system undergoes rapid expansion and is close to both chemical and thermal equilibrium. Thermal equilibrium is thought to be reached very rapidly, but standard hadronic cross sections have difficulty accounting for the rapid rate at which this thermalization occurs.
- Experiments observed a strong enhancement of strangeness production, particularly antistrange particles whose yield would ordinarily be suppressed by their relatively large masses.
- The multiplicity and transverse energy of particles produced in collisions at RHIC have been measured. These measurements provide an estimate of the energy density achieved, which was at least 20 times that of nuclear matter.
- One of the early, unexpected results at RHIC was the strong elliptic flow signal seen at relatively high momenta. A strong elliptic flow indicates that this equilibration developed at very early times when the pressure was very large. Such an early thermalization, combined with the measured transverse energy, implies an energy density substantially higher than that required for the phase transition, as indicated by theoretical lattice calculations.
- In the very dense but very cold environment, quark matter is predicted to display many characteristics more familiar to a condensed-matter physicist than to a plasma physicist: Cooper pairs form, and the quark matter becomes a color superconductor, characterized by Meissner effects and gaps at the quark Fermi surfaces. Such cold quark matter may exist in the centers of neutron stars.

The Phases of QCD



deconfinement (the quarks and gluons become free of their bondage in baryons and mesons)

chiral symmetry restoration (the masses of the quarks are reduced to their bare quarks values)

RECENT ACCOMPLISHMENTS (cont.)

Probing the origin of the elements and the evolution of stars—Two long-term multidisciplinary efforts to develop standard models of Big Bang nucleosynthesis and of the sun have been validated in remarkable ways: The baryon-to-photon ratio derived from analyses of temperature fluctuations in the cosmic microwave background is in good accord with the Big Bang nucleosynthesis prediction, while the total high-energy solar neutrino flux agrees with the standard solar model prediction. Important advances have also occurred in our understanding of nuclear reactions that govern red giant evolution, novae, and supernovae. Improved measurements of $^{12}C(\alpha,\gamma)$ set the luminosity for Type Ia supernovae as cosmological candles and define the limits for the final fate of the Type II supernova core as a neutron star or black hole. Finally, nuclear measurements far from stability and a new generation of computational techniques have brought us closer to the identification of the r-process site, or sites, and to quantitative models for the production of the heavy elements.

- Beams of radioactive nuclei have been used to make the first direct measurements of key nuclear reactions driving cataclysmic explosions in binary systems.
- Elegant experiments using stable and radioactive beams have fueled real progress in understanding the capture of alpha particles on 12 C and the capture of protons on 7 Be, which are of prime importance in the evolution of massive stars and in the core of the sun, respectively.
- By use of neutron beams, the fusion rates of neutrons and heavy elements have been newly determined, yielding the first precise confirmation of the theory that tiny grains in some meteorites originate in red giant stars.
- Supernovae has been numerically exploded.

RECENT ACCOMPLISHMENTS (cont.)

Tracing the missing mass of the universe—Observations of the neutrinos produced in nuclear reactions in the sun have for many years raised doubts about how the sun generates energy: Models of the sun consistently predicted the number of solar neutrinos to be much greater than observed. The solar models were recently vindicated when the SNO and SuperKamiokande experiments found that solar neutrinos change their identity on the way to the Earth, implying that they have mass. This discovery has profound implications: It provides a key to the fundamental structure of the forces of nature, and it shows that neutrinos contribute at least as much mass to the universe as do the visible stars. On the basis of these results, together with measurements of nuclear beta decay, we also now know that neutrinos do not have enough mass to stop the expansion of the universe.

- Oscillations of neutrinos from one type to another have been confirmed as the key to resolving the puzzle of the “missing” solar neutrinos.

RECENT ACCOMPLISHMENTS (cont.)

In search of the new Standard Model—The search for a single framework describing all known forces of nature has been something of a Holy Grail in physics. Accordingly, one of the triumphs of late 20th century physics has been the establishment—and experimental confirmation—of such a framework for three of the four fundamental interactions: the electromagnetic, weak, and strong forces. The Standard Model of electroweak and strong interactions has by now been tested with impressive precision (~0.1% for electroweak phenomena). Despite its successes, however, the Standard Model presents some conceptual difficulties, leading physicists to believe that it represents only a piece of a larger, more fundamental theory. For example, gravity remains to be fully incorporated into a framework including the other three forces, though the advent of string theory represents a breakthrough advance in this regard. In addition, the Standard Model itself contains 19 parameters whose origins and magnitudes are not explained by the theory but rather are taken from experiment. Indeed, the vast hierarchy of masses among the known elementary particles is not explained by the Standard Model. Similarly, the Standard Model gives no reason for the quantization of electric charge, the weak interaction's flagrant disrespect for discrete symmetries (parity, P; charge conjugation, C; and time-reversal invariance, T), or the dynamics responsible for the predominance of matter over antimatter in the universe.

- Measurements of the high-energy neutrino flux from the sun, which have demonstrated that the deficit of low-energy neutrinos on Earth is due to neutrino oscillations, implying that neutrinos have mass. This, together with the discovery of atmospheric neutrino oscillations, will require an extension to the Standard Model of fundamental interactions. This discovery also implies that neutrinos contribute at least as much mass to the universe as do the visible stars.
- A precision measurement of the magnetic moment of the muon, which has helped theorists discover an error in the Standard Model calculation and has placed important constraints on Standard Model extensions, such as supersymmetry.
- Dramatic improvements in experiments on nuclear electric dipole moments and double beta decay. These improvements place stringent bounds on violations of time-reversal symmetry and lepton number conservation.