Nuclear physics at the end of the century

E. M. Henley

Department of Physics and Institute for Nuclear Theory, University of Washington,
Seattle, Washington 98195

J. P. Schiffer

Argonne National Laboratory, Argonne, Illinois 60439
and University of Chicago, Chicago, Illinois 60637

Nuclear physics is the branch of physics that deals with the properties and structure of matter on the hadronic level. This article states a current perspective of the field and of some of the issues that are now on its frontiers. [S0034-6861(99)03502-3]

I. INTRODUCTION

A. Short historical perspective

As we are approaching the turn of the century we wish to review very briefly the status of nuclear physics as it has evolved in the course of our explorations of nature during this period. More first-hand details of this evolution can be found in the article by Hans A. Bethe in this issue (Bethe, 1999).

Nuclear physics was born over 100 years ago with the discovery of radioactivity by Becquerel and followed by the work of the Curies in identifying the sources of the new radiations. The nucleus as a small heavy center of the atom was only deduced in 1911 by Rutherford; its existence was a crucial feature of the Bohr atom—and thus central to the development of quantum mechanics. Until the discovery of the neutron in 1932 it was believed that the nucleus was made of electrons and protons. The nucleus of protons and neutrons, as we know it, can be said to date from that time.

It was quickly realized that to pursue such studies required more intense sources of charged particles. Several classes of accelerators, to provide such energetic particles, were invented and developed for the study of the nucleus in the 1930s, from the electrostatic generators of high voltage by Cockroft and Walton and Van de Graaff, to the cyclotron of Lawrence, to betatrons and their derivatives. Techniques for detecting particles also started in this period, from the early scintillating screens of Rutherford to the counters and cloud chambers of the 1920s and 30s. The early work on nuclear reactions quickly established the size of the nucleus and thus the range of nuclear forces. The electron spectrum of beta decay led Pauli to the supposition that there had to be an additional particle involved, the neutrino, and Fermi subsequently formulated the correct theory of the beta-decay process.

These early developments of nuclear physics provided a rich case study for the application of the new quantum theory.

One of the surprising features of the nucleus was the fact that nuclear forces seemed to have a very short range. In 1935 Yukawa postulated exchange forces and a "meson" as the carrier of the nuclear force that keeps the neutrons and protons bound inside the nucleus. Such a particle, of mass between the electron and proton that was thought to be the meson, was found in cosmic rays in 1937, but it was realized that its nuclear interactions were too weak. We now know that this was the muon, and the pion was not discovered until 1946. The 1930s also saw the first realization by Bethe of how nuclear reactions fuel the sun in converting hydrogen into the light elements.

Progress in nuclear physics was rapid after this start and the last 50 years have seen explosive growth in our understanding of the nucleus, its constituents, and its forces. In the present framework we cannot begin to do justice to many who have made important and often major contributions to the evolution of this part of science and, somewhat arbitrarily, we mention by name only Nobel laureates. The realization in the late 1940s by M. Goeppert-Mayer and J.H.D. Jensen that the structure of the nucleus can be understood in terms of a shell model, as in atomic physics, came as a great surprise because of the high density of the nucleus and the strength of nuclear forces, but the validity of this description has been verified by many phenomena. Its theoretical basis came later.

The large quadrupole deformation of some classes of nuclei led to a further understanding of new degrees of freedom, and the dynamical collective model of Bohr and Mottelson came out of this realization. These degrees of freedom, primarily collective rotations of nonspherical nuclei as well as vibrations, lead to a simplified description, particularly of deformed nuclei. When combined with the shell model in a deformed potential, this work led to a unified model of the nucleus (Bohr and Mottelson, 1969). An important degree of freedom in nuclei was found to be that of "pairing," the correlations between pairs of nucleons coupled to zero spin, and the theoretical understanding has a close analogy with the BCS theory of superconductivity involving the pairing of electrons. More recently, a very successful class of models has emerged, the so-called algebraic models of "dynamic symmetries," that has been given the name of the "interacting boson model." Here the degrees of freedom are those of a boson, primarily of zero spin (Arima and Iachello, 1981). The unified model and the mean-field theories also permitted descriptions of excited states and transition rates. They also led to an understanding of giant resonances seen in the excitation of a nucleus, be they monopole (breathing mode), dipole, or higher multipoles.

In parallel with the vast improvement in our understanding of the structure of nuclei was work on nuclear reactions. Early work showed pronounced resonances in nuclear reactions, particularly the absorption of slow neutrons, indicating long-lived intermediate states. This implied many degrees of freedom and apparently a complicated process. Considerable simplification resulted from models in which the description of the compound system through which a reaction proceeds is described in terms of the *average* properties of the resonances, without detailed consideration of their individual properties. Reactions can be considered in two limits, the first of which proceeds through long-lived intermediate resonances whose decay is independent of their mode of formation—the simple expression for a resonance was given by Breit and Wigner in the 1930s, followed by the detailed treatment in reaction formalisms, particularly of Wigner, in the 1940s and 50s. The other limit, developed in the 1960s, is that of direct, one-step reactions, proceeding in a time comparable to the passage of the projectile through the nuclear volume. In this limit, the reaction may be described by an effective ''optical'' potential with a real and imaginary part. Here the interaction can be described as a perturbation in a quasielastic scattering process with the incident wave modified by the interaction but continuing coherently in the outgoing channel. Formalisms for the descriptions of more complicated reactions between these two extremes were filled in more slowly.

The 1950s and 60s also saw major new developments in beta decay, the realm of the ''weak'' interactions. The ideas of Lee and Yang that parity need not be conserved in beta decay was quickly followed by the work of C.S. Wu showing that, indeed, parity conservation was not a valid symmetry in these processes. The study of nuclear beta decay has laid the foundations of the standard model of elementary particles.

The 1970s and 80s saw the consolidation of the description of the nucleus, with improved experimental techniques supporting the theoretical framework. The use of computers aided this endeavor greatly. The use of heavy-ion beams (accelerated heavy nuclei) was expanded and new features of nuclei were investigated. The use of electron beams for mapping of nuclear-charge distributions, pioneered by Hofstadter, was extended in precision. Distributions of charge and magnetization densities and transition probabilities were mapped out and this field was established as a powerful quantitative source of information about nuclei. More generally, detection techniques evolved considerably in resolution and in the capacity to handle complex information.

New accelerators using superconductivity were developed, both linear accelerators with superconducting rf cavities and cyclotrons with superconducting magnets. Also, the realization of the pion's role in the nucleus lead to the construction of ''meson factories,'' where intense beams of pions were produced for studies of nuclear properties. Strange mesons produced at high-energy accelerators were used to produce ''hypernuclei,'' a new class of nuclei in which a long-lived baryon with a ''strange'' quark is bound along with neutrons and protons.

B. Present perspective

In the current decade (1990s), nuclear physics continues to address the state of hadronic matter, which increasingly includes the structure of hadrons as well as the larger many-body aspects of nuclei. The field of nuclear physics at the end of the century encompasses a number of areas and in this article we will attempt to discuss briefly a few of the current thrusts and cite some review articles that provide more details.

The hadrons are the simplest entities of strongly interacting matter that can exist as free particles. Their properties are well established experimentally, but the way they are constituted out of quarks and gluons is still not well understood. Recent experimental results have shown that the spin of the nucleons, for instance, is not as simple as it seemed a few years ago, but has contributions from the polarization of the ''sea'' of quantum chromodynamics (QCD), arising from gluons and from the possible angular momentum of quarks and gluons. How protons and neutrons—the most stable hadrons—interact with each other to form simple nuclei has seen substantial progress. Evidence is now quite conclusive that simple two-body forces are insufficient to explain the properties of the simple nuclei and that many-body forces are important.

The understanding of the structure of nuclei in terms of the shell model and the various collective rotations, vibrations, and excitations that nuclei undergo has advanced in several directions. In particular, new detection techniques have helped unravel bands of states that correspond to shapes that are deformed from spherical symmetry much more drastically than previously observed—suggesting a region of stability with 2:1 (major to minor) axis ratios. These states appear to be rather pure and hardly mix at all with the more spherical normal states. Other advances in experimental capabilities have allowed physicists to explore the limits of nuclear stability, the so-called drip line.

One of the aspects of QCD that is not satisfactorily understood is the concept of *confinement*, the fact that the constituents of hadrons can never appear as free particles. At very high densities this confinement is expected to break down to the extent that quarks can travel freely within the region of high energy density. This is presumably a state that the universe passed through shortly after the big bang. There will soon be a new tool for investigating the state of matter at that time: a large collider of heavy (e.g., Au) ions is being constructed (RHIC) in which energy densities comparable to the big bang should be reached. A key symmetry that is broken in normal QCD, that of *chiral symmetry*, may well be restored in this regime of energy density. Both the experimental undertakings at this facility and the theoretical interpretations are a major challenge for the field in the coming decade.

The crucial role of nuclear physics in fueling the stars has been recognized since the early work of Bethe, who showed how stars are powered by fusion reactions, and later of Fowler and coworkers who developed the understanding of the processes responsible for the formation of elements. Specific nuclear properties play key roles in the big bang, in the energy production in our Sun and in other stars, and in all the nucleosynthetic processes of the universe. This intimate relationship is beautifully illustrated by the fact that the properties of the lightest neutrinos have been enormously clarified by the theoretical interpretation of experiments that searched for the nuclear reactions that these neutrinos induce on earth.

Finally, not only has the field depended critically on developing a large variety of experimental and theoretical techniques, but these techniques have in turn served society in a number of ways—nuclear medicine being a prominent example.

II. HADRON PHYSICS

The smallest entities of accessible strongly interacting matter in the world are hadrons, either baryons that are aggregates of three quarks or mesons that are made from quark-antiquark pairs. The most stable baryons, the protons and neutrons, are the major constituents of atomic nuclei, and the lightest meson is the pion. Understanding the structure of hadrons and how the properties of these particles arise from QCD is a major interest of nuclear physics. This interest follows two paths. One concerns the properties of families of hadrons as they exist freely, to accurately characterize the members of the rich hadron spectrum in mass and decay properties and reflect the structure that arises from QCD. The other is to understand how these properties change when the hadrons are immersed in nuclei or nuclear matter.

A. Pions

Among the mesons, the lightest and most important one is certainly the pion. Thus, it is no accident that its properties, production, and interactions with nucleons and nuclei have received considerable attention in the past and again at the present time.

Because quantum chromodynamics (QCD) is the underlying theory of hadronic interactions, there have been many models built on one aspect or another of the theory. A particularly important symmetry of QCD, which is almost preserved at low energies, is chiral invariance or the symmetry between left and right handedness. (This differs from parity, which is invariance under mirror reflection.) Chiral symmetry is incorporated into the most recent treatments of few-body problems, with the use of low-energy effective theories, such as chiral perturbation theory, first introduced by Weinberg many years ago (Weinberg, 1979). Here an effective Lagrangian is constructed which incorporates all terms allowed by the symmetries of QCD. In QCD with massless up (u), down (d), and strange (s) quarks, the theory satisfies chiral invariance. This leads to both conserved-vector and axial-vector currents and to parity doublets. Since the axial current is not conserved in nature and parity doublets are not observed, one assumes that spontaneous symmetry breaking leads to the eight Goldstone (almost massless) pseudoscalar bosons. The finite quark masses also break the symmetry somewhat, and this leads to the nonvanishing pion and other light pseudoscalar-meson masses.

TABLE I. Magnitudes of the amplitude for photoproduction of pions in units of $10^{-3}/m_{\pi}^{+}$ to lowest ($n=1$) and higher ($n=2$ and 4) order in a chiral-perturbation-theory expansion compared to experiment (Holstein, 1995).

Amplitude	$n=1$	$n=2$	$n=4$	Experiment
$\gamma p \to \pi^{+} n$	34.0	26.4		28.4 ± 0.6
$\gamma n \to \pi^{-} p$	−34.0	−31.5		-31.8 ± 1.2
$\gamma p \to \pi^{0} p$	0	−3.58	−1.16	-1.31 ± 0.08
$\gamma n \to \pi^{0} n$	0	0	−0.44	~ -0.4

The approximate chiral invariance is incorporated in all low-energy effective theories. Chiral perturbation theory is a low-energy theory with a systematic expansion around the chiral limit in powers of m_{π}/Λ and p/Λ, where p is a typical momentum of order m_{π} or less and Λ is a QCD scale, of the order of 1 GeV. Because it is an effective theory, it needs to be renormalized at each order of the expansion. One introduces an effective operator in terms of the pion field. The most general Lagrangian density is then unique. When expanded in terms of m_{π}/Λ and p/Λ, the free-pion Lagrangian is obtained to lowest order and pion-pion scattering is found at the next order. Although the agreement with experiment is quite good, even at this order, it is improved by continuing the expansion through the inclusion of higher-order terms (Holstein, 1995).

Recently the photoproduction of pions has received considerable attention because it is a test of chiral perturbation theory. At threshold the production mechanism is dominated by the electric dipole amplitude which is given by gauge invariance (Ericson and Weise, 1988). In chiral perturbation theory the production amplitude is independent of the pion mass and the pion-nucleon coupling constant. At this order, the π^0 photoproduction from protons and neutrons vanishes. But at the next order, an expansion in terms of m_{π}^{2}/Λ^{2} and $(p/\Lambda)^{2}$ gives a finite value which agrees quite well with recent experiments (Bernstein and Holstein, 1991, 1995; Holstein, 1995). Higher-order calculations do even better. We compare theory and experiment in Table I.

B. Nucleon structure

While we know that nucleons and mesons are composed of quarks and gluons, the transition from a description of nuclei in terms of nucleons and mesons to one in terms of quarks and gluons is still not understood. Nor do we fully understand the structure of the nucleons and mesons. Progress has been made by solving QCD numerically on a finite lattice rather than in continuous space-time.

In an effective theory the gluon degrees of freedom do not appear explicitly; in some models they are incorporated in the dressing of the quarks, which then are called constituent quarks. The constituent quarks (up and down) have masses close to one-third of the mass of the nucleon and thus have small binding energies. There are models of the nucleon made up of such quarks, often treated nonrelativistically and bound by harmonic or other simple forces. These models are amazingly successful in predicting the ratio of the proton to neutron magnetic moments. However, a number of authors have pointed out that this result is not very model dependent. Most effective theories (e.g., chiral perturbation theory) use almost massless "current" quarks.

One of the original motivations for the study of nuclear structure was to gain an understanding of the strong interaction. Following this interest in the structure of hadronic matter, nuclear physicists have become more and more interested in a quantitative understanding of the structure of hadrons. QCD provides the framework for such understanding. For instance, QCD-based constituent quark models not only can reproduce accurately the masses of mesons with heavy quarks, but can also account for the main features of the masses and electromagnetic decays of baryons with light quarks. However, significant problems remain. In particular, some signs and magnitudes of strong decays of the higher-mass nucleon resonances are poorly understood, possibly because of the lack of a proper treatment of chiral symmetry. The lack of clear experimental evidence for particles that would correspond to excitations of the gluonic field or "hybrid" states of baryons that involve involve gluonic excitations is another outstanding puzzle.

In the last few years deep-inelastic polarized electron scattering on polarized H and D targets have provided insights into the spin structure of the nucleon and revealed that we do not yet fully understand it. For a given quark (q) species (u, d, or s) the fraction of the nucleon's spin that is carried by quark spins is defined as

$$\Delta q \equiv q\uparrow - q\downarrow + \bar{q}\uparrow - \bar{q}\downarrow, \tag{1}$$

and the total spin carried by the quarks is

$$\Delta\Sigma = \Delta u + \Delta d + \Delta s, \tag{2}$$

with

$$\Delta u - \Delta d = g_A, \tag{3}$$

where g_A is the weak axial-vector coupling constant, and arrows indicate spins parallel (↑) and antiparallel (↓) to the proton's spin. The nonrelativistic "naive" constituent quark model predicts

$$\Delta u = 4/3, \quad \Delta d = -1/3, \quad \Delta s = 0, \quad \Delta\Sigma = 1, \tag{4}$$

and

$$g_A = \Delta u - \Delta d = 5/3. \tag{5}$$

Equation (5) turns out to be far from the truth. Neutron beta decay yields $g_A = 1.26$ and the deep-inelastic scattering experiments show that only about 30% of the spin of the proton comes from the quarks. It is found that (Ashman *et al.*, 1989; 1997)

$$\Delta u = 0.84 \pm 0.04, \quad \Delta d = -0.42 \pm 0.04,$$
$$\Delta s = -0.09 \pm 0.04, \quad \Delta\Sigma = 0.33 \pm 0.08. \tag{6}$$

The experimental result came as a surprise and was called the "proton spin puzzle"; it implies that the major fraction of the proton spin comes from the gluons and possibly from orbital angular momentum. However, Δq is generally evaluated in the infinite-momentum frame and the nonrelativistic quark model is for a nucleon at rest. In terms of mesons, the angular momentum could come from pions coupled to quarks.

Another surprise was the relatively large ($\sim$10%) contribution to the spin from strange "sea" quarks. These are quarks and antiquarks in equal numbers that are in addition to those ("valence" quarks) that make up the charge of the nucleons. Again, in principle, this can be understood in terms of low-energy nuclear physics via the dissociation of protons into strange baryons and mesons such as Λ and K^+. Antiquarks play a role because gluons can split into $q\bar{q}$ pairs; the $\bar{q}$ can combine with valence quarks to form pions. To the extent that the QCD Fock space includes (nonperturbative) pions, one can understand the excess of $\bar{d}$ over $\bar{u}$ in a proton since a one-meson decomposition gives $p = p\pi^0$ or $n\pi^+$, with a $\pi^+ = u\bar{d}$. Indeed, there is evidence for an excess of $\bar{d}$ over $\bar{u}$ in the proton from inclusive hadronic reactions with lepton pair production (Drell-Yan processes) and from tests of the "Gottfried sum rule," which follows from the assumption of a flavorless sea of light quarks ($u\bar{u} = d\bar{d}$ in the sea).

C. Nuclear forces

The nucleon-nucleon force is basic to understanding nuclei and thus has been of great interest for many decades. Broadly speaking, potential representations of the force are either purely phenomenological, or based on meson exchange but with the parameters determined phenomenologically. All models have a one-pion exchange character at long range, which gives rise to a spin-spin central potential and a tensor term. The correctness of pion exchange and its dominance at large distances is clear from the nucleon-nucleon phase shifts at large angular momenta and from various properties of the deuteron ground state, such as the nonzero quadrupole moment. Indeed, the strong tensor component of the pion-exchange force is a unique feature that makes the solution of nuclear many-body problems particularly challenging.

Some potential models represent the shorter-range interaction by heavy-meson exchanges. The Reid and the

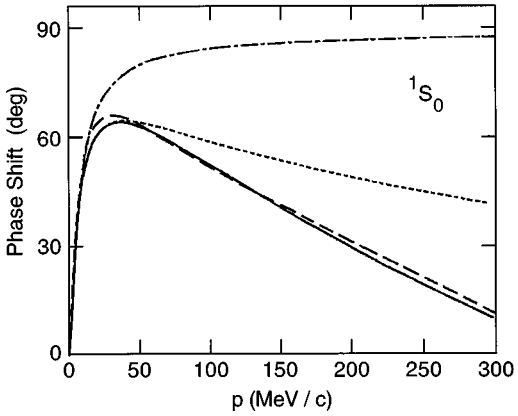

FIG. 1. The phase shift δ for the $^1S_0$ channel. The dot-dash curve is a one-parameter fit in chiral perturbation theory at lowest order. The dotted and dashed curves are fits at the next order in the expansion; the dashed one corresponds to fitting the phase shift between $0 \leq p \leq 200$ MeV, whereas the dotted one is fit to the scattering length and effective range. The solid line corresponds to the phase shift obtained from a partial wave analysis carried out by the Nijmegen group (Kaplan, Savage, and Wise, 1998).

Urbana-Argonne potentials are examples of more phenomenological models, while the Nijmegen, Paris, and Bonn potentials are based more on meson exchange (Ericson and Weise, 1988; see also Machleidt, 1989). In the last few years significant progress has been made in obtaining high-precision fits to the elastic-scattering data. The "Argonne V_{18}," the "CD Bonn," and several Nijmegen models all fit these data within the experimental accuracy.

These modern potentials, coupled with recent advances in nuclear many-body theory and in the capacity of computers, now makes it possible to understand the stability, structure, and reactions of light nuclei directly in terms of nucleons. Three- and four-nucleon systems are studied accurately in both bound and scattering states by Faddeev and hyperspherical harmonic methods. For nuclei with up to 7 nucleons, quantum Monte Carlo methods have been applied successfully. Ground states, stable against breakup into subclusters, are determined for ^{6}Li and ^{7}Li, and their binding and excited-state spectra agree reasonably. In this work three-nucleon forces are required; their strength is adjusted to reproduce the binding energy of ^{3}H and to give a reasonable saturation density for nuclear matter (Carlson and Schiavilla, 1998).

Chiral perturbative theories and other effective theories have also been applied to the nucleon-nucleon problem. Despite the difficulty caused by the large scattering length that characterizes the data for the $^1S_0$ state, and the bound $^3S_1$ states, these theories fit the phase shifts very well up to momenta of 300 MeV/c (see Fig. 1). The effective potentials or interactions include a contact term and pion exchange. Related techniques with effective chiral theories have been used by others (Meissner, 1992). It is interesting that chiral perturbation theory allows one to show that three-body forces are smaller than two-body ones by the ratio $(p/\Lambda)^2$, where p is a nucleon momentum and Λ, as before, is a QCD scale; for example, if the two-body potential has an average strength of 20 MeV, then the three-body one would have a strength of about 1 MeV. A nice feature of chiral perturbation theories is that they can rank the various classes of charge-independence and charge-symmetry breaking forces in powers of p/Λ.

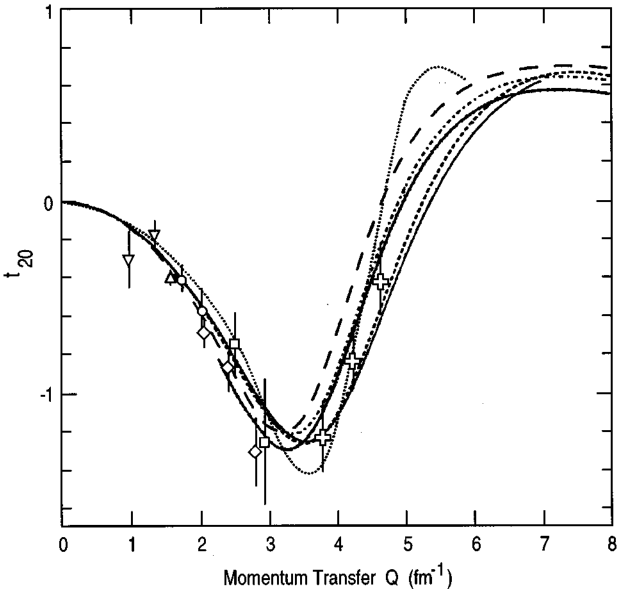

FIG. 2. The results of polarization measurements from electron scattering from the deuteron. The quantity t_{20} from a variety of experiments is shown by different symbols, with predictions of different theoretical models of the nucleon-nucleon interactions drawn by lines. New measurements from CEBAF should help to better distinguish between the models.

Very sensitive tests of the nucleon-nucleon interaction in bound states are precise measurements of the radial distribution of nucleons in nuclei for comparison with *ab initio* calculations (Carlson, Hiller, and Holt, 1997). In many cases electron scattering can measure these distributions directly. However, in the case of the deuteron, which has unit spin, the orbital angular momentum 0 and 2 contributions can be separated using polarized electron-deuteron scattering in the tensor-polarization observable t_{20}. The current information on this quantity is illustrated in Fig. 2. A measurement that should provide such information to momentum transfer $Q > 6\ \mathrm{fm}^{-1}$, or about 0.15 fm in the distances in the radial distribution of the deuteron, is among the early experiments with the CEBAF electron accelerator.

While these measurements demonstrate the wide validity of the hadronic description of the deuteron, at the shortest distance scales the nucleon substructure does become important. To date, one nuclear reaction, the photodisintegration of the deuteron at large transverse momenta into a proton and a neutron, shows the behavior expected of coherently transferring the energy of the incident photon to the six constituent quarks in the deuteron. Indeed, this reaction seems to show "counting rule" behavior at considerably lower energies than was

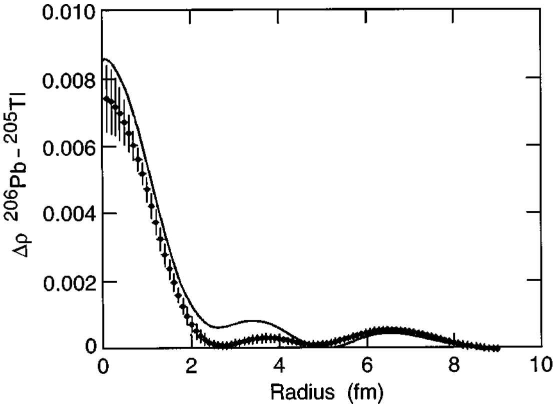

FIG. 3. Difference in charge densities between ^{206}Pb and ^{205}Tl and oscillations due to the radial nodes in the wave function of the last proton (Pandharipande, Sick, and de Witt Huberts, 1997). The line is a Hartree-Fock calculation of the same difference.

expected, suggesting a wider validity for quark descriptions.

III. NUCLEI

The understanding of the structure of nuclei is in terms of models, such as the shell model and the collective model, that necessarily involve approximations in the characterization of a finite many-body system with complex forces between the constituents.

The use of the Hartree approximation with simplified potentials representing the nucleon-nucleon interaction, or even a field theory with scalar and vector mesons ("quantum hadrodynamics") leads to a mean field in which the nucleons move. The theory can be extended to Hartree-Fock and to include deviations from the mean field; it can be compared to experiment. For instance, it does well in reproducing the charge density determined by electron scattering as is seen in Fig. 3.

Electrons are a great tool for precision studies of nuclei: their interaction is sufficiently weak that perturbation theory can be used, they cause little distortion of the system, and their wavelengths can be made sufficiently short to study both nuclei and nucleons in detail (Diepernick and de Witt Huberts, 1990). Electron scattering beautifully shows the single-particle structure of nuclei in a mean-field description by measuring the properties of individual shell-model orbitals and also by exploring the limitations of this description because of the correlation effects that arise from the short-range part of the nucleon-nucleon interaction (Pandharipande, Sick, and de Witt Huberts, 1997). This is clearly seen in the proton-knockout reactions illustrated in Fig. 4. The consequences of these correlations are manifold. They substantially renormalize the single-particle mean-field orbitals and appear to be the source of high-momentum nucleons that are important in "subthreshold" production of mesons and other particles (e.g., antiprotons). Such correlations can have an effect on the mean-free paths of nucleons and other hadrons in nuclei and on mechanisms responsible for pion absorption in the nuclear medium. But we are only at the beginning of being able to separate the effects of short-range correlations from other many-body effects, both experimentally and theoretically.

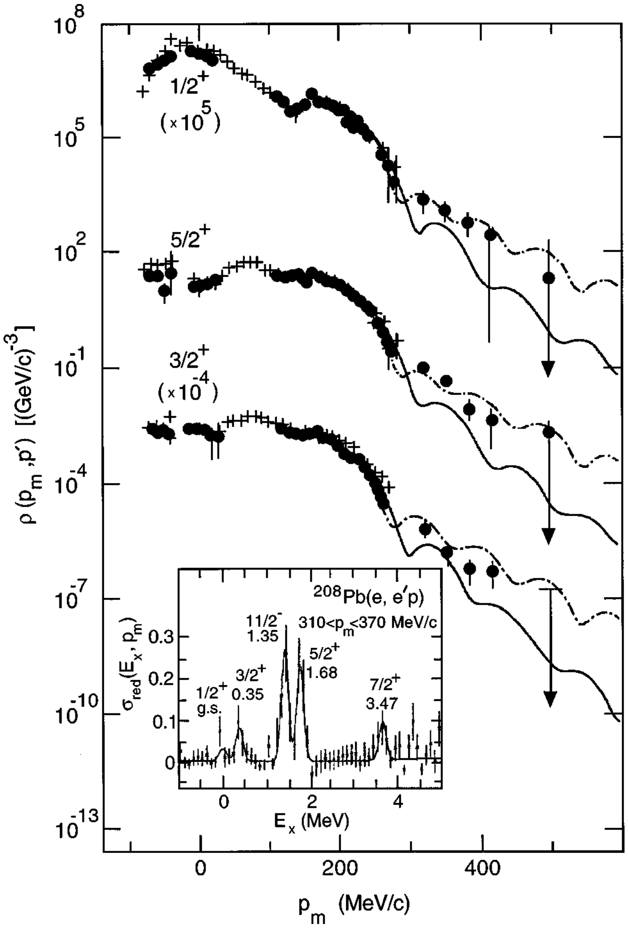

FIG. 4. Demonstration of high-momentum components in the nuclear wave function. Transition densities from electron scattering knocking out a proton from the single-particle states in the doubly-magic nucleus ^{208}Pb. The inset shows the spectrum of hole states. The solid line represents the transition density calculated using a mean field for the protons, the dot-dashed curve includes the effects of short-range, high-momentum correlations (Pandharipande, Sick, and de Witt Huberts, 1997).

Another perspective of the single-particle structure in nuclei with many nucleons comes from an entirely different dimension. While the successes of the single-particle description in heavy nuclei are remarkable, the description is tested almost entirely for the "valence" orbitals and not for the deeply bound states. Such tests become possible by introducing a different baryon into the nucleus that can settle into the lowest state without violating the exclusion principle. The most suitable baryon, because of its relative stability, is the Λ, and the structure of the deeply bound states of the so-called "hypernuclei" beautifully confirm the single-particle description with the mean field modified to account for the differences in the Λ-nucleon interaction (Chrien and Dover, 1989).

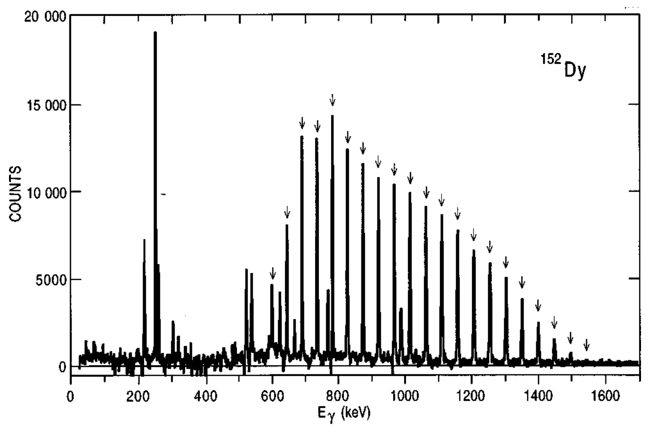

FIG. 5. A "superdeformed" rotational band in ^{152}Dy showing the gamma-ray transitions between members of the band. The constant increments in gamma-ray energies are characteristic of a band that follows the symmetry of a very good quantum-mechanical rotor. The variation in intensity of these gamma rays reflects the angular momentum distribution in the population of the band in the fusion-evaporation reaction that was used. The peaks that are not indicated by arrows correspond to states of lower energy of "normal" deformation, populated after the decay out of the super-deformed band (Twin *et al.*, 1986).

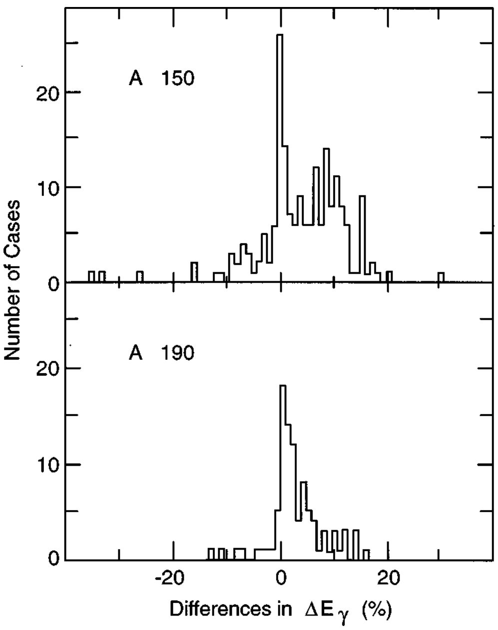

FIG. 6. Similarities between superdeformed bands in nuclei in the same vicinity. The quantity plotted is the mean percentage difference in $E_\gamma(J+2\rightarrow J)-E_\gamma(J\rightarrow J-2)$ between different bands. About sixty bands within the mass 150 region and fifty bands within the mass 190 region are compared. Note that in both regions there is a large excess of pairs of bands for which this quantity differs from zero by less than 2%—these are the "identical bands"—others differ by up to 20%. This identical reproduction of bands in different nuclei is not yet fully understood.

Major advances have been made recently in exploring the structure of nuclei in the limits of extreme conditions—at very high angular momentum, in approaching the limits of nuclear binding, and in temperature and energy density (discussed in Sec. V). We discuss the first two in the section below, as examples of recent developments in the field. The advances in approaching these limits have come in recent decades from novel and substantially improved experimental techniques coupled with new theoretical understanding.

A. Nuclei at high angular momentum

Accelerator developments have enormously expanded available beams. Beams of heavy nuclei, accelerated as projectiles, have made it possible to bring large amounts of angular momentum into nuclei (Diamond and Stephens, 1980). For instance, with a 200-MeV ^{48}Ca beam incident on a target of ^{120}Sn one forms a compound nucleus at high excitation energy, that first rapidly decays (in $\sim 10^{-21}$ sec) by emitting particles (neutrons), and then remains highly excited in a bound system, usually with high angular momentum. In a rotating reference frame, the excitation energy is not very high—it has to be measured with respect to the lowest energy that the nucleus can have at this angular momentum (the so-called "yrast line"). Under the influence of centrifugal forces the lowest configurations in the nucleus can be quite different from those at low angular momentum. The shell structure of nuclei becomes rearranged under the centrifugal effects of rotation and new pockets of relative stability, in the potential-energy surface of the nucleus, may develop as a function of quadrupole deformation. This then results in new classes of nuclear states, with high deformation, in which many of the nucleons have microscopic quantum numbers that are different from those of the ground state.

The exploration of nuclear structure at high angular momentum has shown that a few percent of the time fusion reactions populate states that decay by electromagnetic cascades which show characteristic rotational bands of remarkable simplicity as is shown in Fig. 5. The energy spacings in these bands correspond to nuclei with much higher deformations (2:1 axis ratios) than those in the normal deformed bands that had been the basis of the collective model of Bohr and Mottelson (typically 1.3:1 axis ratios). The exploration of the properties of these *"superdeformed"* bands (Nolan and Twin, 1988; Janssens and Khoo, 1991) has uncovered a great deal of structural information. The precise energies in these, including the microscopic details of the small deviations from the pattern expected of perfect rotors, are reproduced with surprising accuracy in several nearby nuclei, giving rise to the *identical-band* phenomenon (Baktash, Haas, and Nazarewicz, 1995) as is illustrated in Fig. 6. It seems that these microscopic signatures carry over from one nucleus to another, without change, in a way that has not been seen elsewhere in nuclear structure and is not fully understood.

One of the most interesting features of superdeformed bands, mentioned above, is the fact that even when these states are well above the yrast line, they hardly mix at all into the higher-density states with more "normal" deformations. There appear to be two distinct classes of states corresponding to two minima in the potential-energy surface, with different deformations. The superdeformed states are closely related to a class of states that appeared in the 1960s in the study of delayed fission of very heavy nuclei. The mixing between these states leading to fission and the ordinary states is similarly inhibited.

The discovery and study of these phenomena in nuclei at high angular momentum have become possible through major advances in the detection and precision energy measurement of gamma rays with high-resolution germanium diodes. The size of the detectors, and their anticoincidence shields to suppress the Compton-scattering background, have now been developed to the point where complete spheres of detectors are used to search for multiple coincident gamma rays from a cascade. This instrumental advance culminated in detectors such as Gammasphere in the U.S. and Euroball in Europe. The new experimental information, in turn, has led to major advances in the theoretical insights into the structure of nuclei at the limits of large centrifugal stress.

Experimental work with these new instruments has also led to other new discoveries. One of the most interesting of these are bands of states connected by radiative transitions whose energies increase in small smooth increments, very much as those for rotational states (Baldsiefen *et al.*, 1995). However, unlike the electric quadrupole radiations that are the earmark of transitions within rotational bands, the gamma-ray transitions in these sequences are magnetic dipole in character. This came as a dramatic surprise. The plausible explanation for these magnetic transitions is that there are two, rather stable, configurations, one for protons and one for neutrons, each of large angular momentum. The sequence of states with increasing angular momentum then correspond to states where the angular-momentum vectors of the two configurations simply are reoriented, as the closing blades of shears, to be more nearly parallel and thus give higher total angular momentum. This explains the large magnetic dipole transitions, but the smooth dependence to the sequence of energies is still very much a puzzle. The phenomenon suggests that some cooperative collective features are present, though theoretical understanding is still not complete.

B. Limits of binding

The 1950–1980 period saw the systematic exploration of the structure of nuclei in and near the valley of nuclear stability through a variety of techniques. The limits of nuclear binding, where for a fixed number of protons no more neutrons can be bound (or for a fixed number of neutrons no more protons), the so-called "drip lines" were largely unknown, except for the lightest nuclei. The drip lines are of interest because nuclear properties might change, especially near the neutron drip line. They are also of particular interest in various stellar processes where, in a hot environment, a sequence of captures takes place rapidly. With recent advances the exploration of these limits has started in the 1990s.

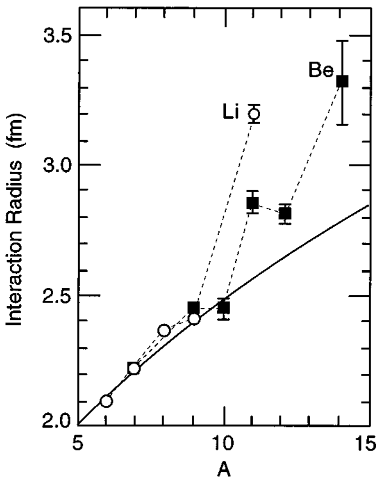

FIG. 7. Interaction radii of Li (3 protons) and Be (4 protons) nuclei with carbon derived directly from total cross-section measurements. The line represents a smooth $A^{1/3}$ dependence of the radius (Tanihata, 1995).

One new phenomenon that occurs along the drip line is the observation of proton radioactivity, where the nuclei are literally dripping protons because their binding is insufficient but the Coulomb barrier retards their emission. At present, these have been identified in a number of elemental isotopic sequences, from Co to Bi, and the structure of these nuclei at the proton drip line is beginning to be explored (Woods and Davids, 1997).

Another result is in the limit of neutron binding where much less is known, because this regime is much more difficult to reach in laboratory experiments. Since neutrons see no Coulomb barrier, the density distributions of loosely bound neutrons can have long tails that reach far beyond the "normal" nuclear radii. These exponential tails fall off more and more slowly with decreasing binding energy. Thus the neutrons will reach far beyond the proton distributions in very neutron-rich nuclei. Such a separation between neutrons and protons, might in turn cause some qualitative changes in nuclear properties. For instance, it has been suggested that the spin-orbit term may be substantially reduced in such nuclei, and this would cause a change in shell structure that would be very interesting to observe experimentally. Such a change could also have serious consequences on the rapid neutron capture, r-process, in explosive stellar nucleosynthesis.

The best current example of a nucleus with diffuse neutron excess is in the very light nucleus ^{11}Li with three protons and eight neutrons. Here experiments show clearly how the last two, very loosely bound, neutrons form a diffuse tail, a "halo" around the protons. Thus the interaction radius of this nucleus is substantially larger than that of other Li isotopes as is shown in Fig. 7 and the structure of what would be the electric-dipole giant resonance in other nuclei is substantially different here, as is the momentum distribution (Hansen, Jensen, and Jonson, 1995). The further exploration of very neutron-rich nuclei, beyond the very light ones, requires major new advances in experimental techniques and facilities.

Another limit being explored is that of total mass, or nucleon number. Here ingenious improvements in experimental techniques permit the production of ever heavier new isotopes and elements, beginning to approach the region where calculations predict that, because of the stabilizing effects of shell structure, a new island of relatively stable "*superheavy*" nuclei should occur. A few nuclei of the new element with $Z=112$ have been produced—near one such possible island with $Z=114$, but further from another suggestion with $Z=126$. The results may in fact indicate a relatively stable bridge leading to a more stable island. Very heavy atoms are also of interest in QED, as they allow an exploration of vacuum polarization, and other relativistic effects under extreme conditions (Hofmann, 1996).

C. Hadrons in the nuclear medium

A crucial assumption in most many-body descriptions of nuclei is that nucleons and other hadrons do not change in the nuclear medium. Deep-inelastic scattering of electrons on nuclei has given evidence that nucleons and their quark structures are altered somewhat when they are placed in nuclei (Geesaman, Saito, and Thomas, 1995). This is called the EMC effect after the group that discovered it. Their finding has stimulated experimental and theoretical studies of these changes and, more generally, has raised important issues about how the properties of hadrons change in the hadronic medium of a nucleus. The changes can be investigated at the quark level in high-momentum-transfer reactions and at the hadron level in both electron scattering and heavy-ion collisions. Using electrons, the elastic form factors of the proton and neutron inside nuclei have been compared to those of free protons and neutrons in deuterium. Intriguing differences in the ratio of the magnetic to electric properties of the proton in light nuclei have been observed, and this is an active area of investigation.

On the other hand, there is clear evidence for changes in the effective nucleon-nucleon force in the nuclear medium. The challenge is to distinguish "normal" many-body effects from changes in the hadronic substructure. For instance, how do virtual pions from pion exchange manifest themselves in a change of the sea antiquark distribution of nucleons in nuclei? This is being examined at the hadronic level in looking for pions knocked out by electrons, in Drell-Yan processes that are directly sensitive to antiquarks, and in looking for pionic modes excited in proton scattering. If the structure and properties of the mesons change in the nuclear medium, there may be important implications for the effective internucleon forces.

These changes involve not only pions but also vector mesons. Theorists have suggested that the masses of the latter should decrease (Adami and Brown, 1993; Ko, Li, and Koch, 1997), but this remains controversial. The width of the ρ resonance is also likely to be affected. These alterations can be sought by searching for the leptonic decays of the vector mesons produced in heavy-ion collisions and studying their leptonic decays within the nucleus. Such experiments are being undertaken. Many of the changes of hadrons are not large, but the methodology seems to be at hand to seek them out and the consequences could have a profound impact throughout nuclear physics.

When a colorless hadron is produced in a high-momentum-transfer reaction, the hadron is small at birth. Due to color screening of the quark components of this small hadron, its mean free path in the nucleus is large and its final-state interactions small. This phenomenon is called color transparency (Miller, 1994), and should be visible in quasielastic (e,ep) and (p,pp) reactions on a nuclear target. At present the evidence for nuclear transparency is ambivalent and further experiments are required to tie the effect down.

IV. NUCLEAR ASTROPHYSICS

Nuclear physics plays a key role in the processes that take place in the universe, from the big bang on to energy production in stars. The synthesis of the chemical elements in the universe is the result of the various nuclear reactions that take place in different stellar environments. The Big Bang produced mostly protons and some of the lightest elements. When stars are formed from these remnants of the Big Bang, their matter is heated as the star contracts under gravity. In the hot star, nuclei run through cycles of nuclear reactions and hydrogen is gradually converted into helium, as in our sun. Somewhat hotter stars will form carbon, and as the carbon cycle described by Bethe becomes important more hydrogen is converted into helium. Further heating will cause captures of protons and alpha particles beyond the carbon cycle. Under appropriate conditions these reactions will produce elements up to about mass 56. To get further in mass, neutron capture is essential—and this can happen slowly in the "s-process" or explosively in the cataclysmic "r-process." All the elements heavier than iron in our world were produced in such stellar environments. Below we mention only a few of the key developments in our understanding of the recent past—following the major insights in this field by Bethe, Fowler, and others in identifying how nuclear processes determine the evolution of matter in the universe, in describing energy production in the Sun, and in explaining the formation of the elements from the Big Bang through the stages of stellar evolution.

A. Solar neutrinos

One of the intriguing developments of the past decades has been the study of neutrinos from the Sun. Other than the heat radiated, the neutrinos are the one accessible observable product from the chain of nuclear

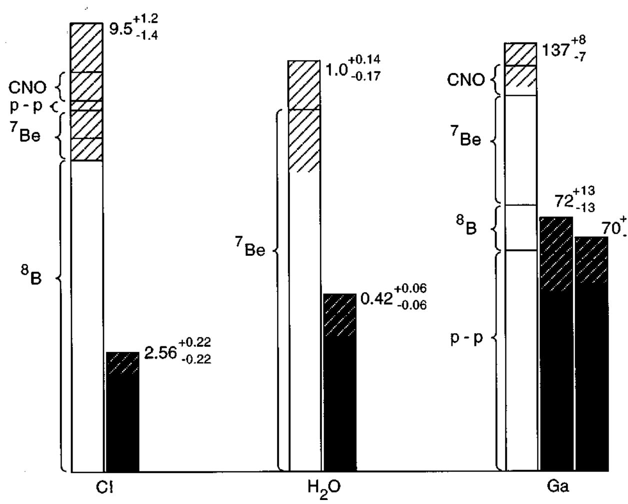

FIG. 8. The solar neutrino signal expected with three different detection methods that are sensitive to different neutrino energies. The light bars indicate the expected neutrino yield, in appropriate units, from the various sources in the solar cycle. The solid bars represent the observed signals from the corresponding experiments. The shaded areas represent the uncertainties.

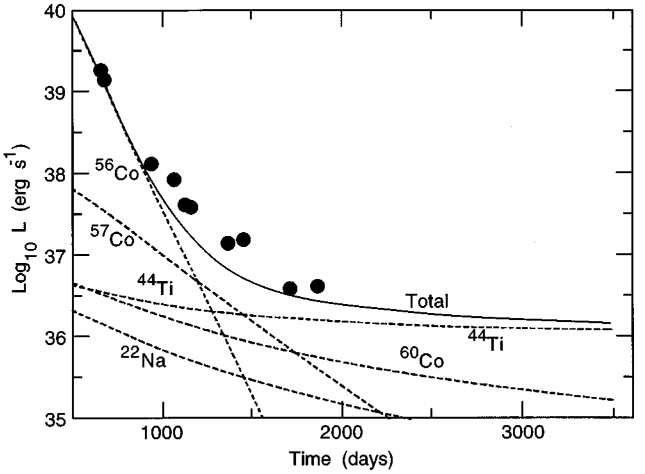

FIG. 9. The logarithm of the light intensity from the supernova SN1987A as a function of time after the supernova explosion. Most of the intensity for the first two years comes from ^{56}Ni and its daughter ^{56}Co. The calculated contributions from other radioactive nuclei are also shown.

processes that take place in the interior. It was noted early that the number of neutrinos detected on earth was too small, given that the energy output of the sun is known accurately and thus the number of nuclear reactions leading to neutrinos is also known. The pioneering experiments of Davis and colleagues with a chlorine detector in the Homestake mine in South Dakota were sensitive primarily to the highest-energy neutrinos, those from the decay of ^{8}B. The observed neutrino flux was about a third of that expected, and in spite of extensive measurements and remeasurements of the nuclear parameters relevant to the solar processes and to the detection scheme, the discrepancy remains today as is shown in Fig. 8.

More recent experiments with gallium as the detecting material, in Europe and Russia are sensitive to much lower-energy neutrinos. They also find substantially fewer neutrinos than expected, as do experiments in which the high-energy neutrinos are detected more directly in large water detectors in Japan. The combined impact of these very different experiments has already been profound. The deficiency in the number of electron neutrinos might have its origins in the possibility that neutrinos have finite mass and that they oscillate between the originally emitted electron neutrinos and neutrinos of other flavors, with this oscillation enhanced by their passage through the dense matter of the Sun. Whether this is indeed the case will be tested in experiments to be carried out in the coming years (Haxton, 1995).

In a recent report of the Kamiokande experiment the signals from muon and electron neutrinos from cosmic rays were analyzed, rather than those from neutrinos coming from the sun. They appear to show neutrino oscillations, apparently $\nu_\mu \rightarrow \nu_\tau$, and thus also give tantalizing indications of neutrino mass and oscillations.

B. Supernovae

Among the most spectacular events in the universe are the supernova explosions that occur under the right circumstances during the evolution of sufficiently massive stars. The dynamics of such an explosion involves a complex interplay between nuclear properties, gravity, and the weak interaction. Supernovae play by far the dominant role in the synthesis of heavy elements. The decay in the light curve of a supernova, shown in Fig. 9, is governed predominantly by the decay of ^{56}Ni—the progenitor of ^{56}Fe, the most tightly bound nucleus and the most abundant element constituting the earth. The enormous flux of neutrinos from supernovae was evidenced by the dramatic detection of a neutrino pulse from the supernova SN1987A. Recent theoretical work has shown that the shock front of neutrinos interacting with nuclear matter plays a major role in the dynamics of supernova explosions.

C. Neutron stars

A typical neutron star has about 1.4 solar masses compressed in a sphere of 10 km radius. More than 500 neutron stars have been detected in our galaxy, most as radio pulsars and some at optical and x-ray wavelengths. A dozen neutron stars are found in close binary pairs, which has allowed their individual masses to be measured very accurately through orbital analysis. Binary neutron star coalescence events may be the source of observed extragalactic gamma-ray bursts, and our best hope for directly detecting gravitational radiation.

The structure of a neutron star is a consequence of the interplay between all interactions: the strong nuclear force, electroweak interactions, and gravity, with significant corrections from general relativity. The surface is metallic iron, which is the most stable form of matter at zero temperature and pressure. Underneath is a lattice of nuclei that grow progressively larger, more neutron-rich, and more tightly packed as the density increases with depth, since it is energetically favorable to capture electrons on protons to reduce the kinetic energy of the electron gas. At about 4×10^{11} g/cm^3 matter density, neutrons start to leak out of the nuclei, forming a low-density neutron superfluid in the intervening space. As the density increases further, around 10^{14} g/cm^3, various unusual shapes of nuclei may occur, with transitions from spheres to rods to sheets to tubes to bubbles. Eventually at a density around 2.7×10^{14} g/cm^3, or normal nuclear matter density, the nuclei dissolve into a uniform fluid which is over 90% neutrons, 5–10 % protons and an equal number of electrons to preserve electrical neutrality, all in beta equilibrium. At successively higher densities muons, and perhaps pions and/or kaons may be present. At high enough densities, quark matter will probably appear, perhaps initially as bubbles in the nucleon fluid.

Progress in characterizing the nucleon-nucleon interaction has been key to our increased understanding of dense nucleon matter and consequently of neutron star structure. If neutrons were noninteracting, the maximum neutron star mass stable against gravitational collapse to a black hole would be 0.7 solar masses. However, many neutron stars have been observed with masses 1.3–1.6 times the solar mass, so the role of nuclear forces is clearly important. Recent work has set the minimum upper limit on neutron star mass at 2.9 solar masses, helping to further refine the observational boundary between neutron stars and black holes. Observations of quasi-periodic oscillations in binary x-ray sources may also soon lead to limits on neutron star radii, which will give an even tighter constraint on the dense-matter equation of state.

D. Nucleosynthesis and reactions with unstable nuclei

The nuclei of the chemical elements are formed in the very hot environment inside stars. At higher stellar temperatures, these processes occur sufficiently fast that the nuclei involved are themselves short lived. New tools are being developed to determine properties of these short-lived nuclei, including the cross sections that are likely to be most important in astrophysical contexts. In addition, there are some expectations that the general features of nuclear structure may change near the limits of binding, where the path of explosive nucleosynthesis takes place.

The enormous improvements in the observational techniques of astronomy and astrophysics inevitably will require better quantitative understanding of the nuclear processes that yield energy in the universe and form an intriguing interface with nuclear physics.

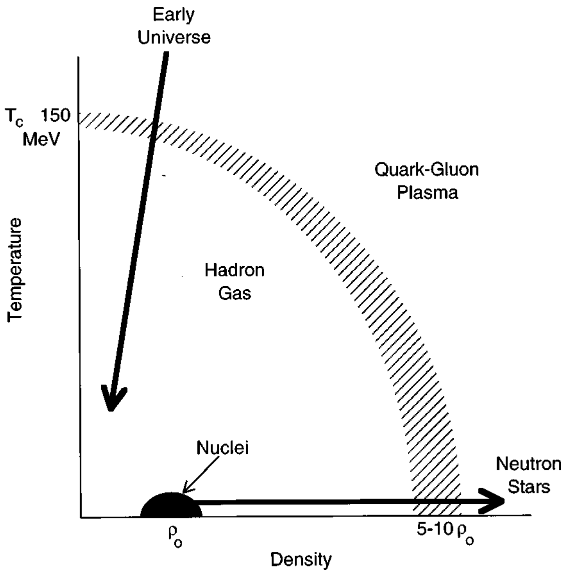

FIG. 10. A qualitative phase diagram for hadronic matter showing the transition to a deconfined quark-gluon state at high temperature and high density. The paths followed in the early universe and in the interior of neutron stars is also indicated. ρ_0 is the density of normal nuclei. Collisions in the relativistic heavy-ion collider RHIC will explore this phase diagram in detail.

V. MATTER AT HIGH ENERGY DENSITIES

One of the areas of intense interest is associated with the physics of very high densities, where the description of matter in terms of quarks and gluons contained in individual hadrons must break down. Calculations based on QCD suggest that when high densities and temperatures are reached in a volume large compared to that of a typical hadron, a transition to a state of matter will occur where the quarks are no longer confined to their individual hadrons but can move freely within the larger volume.

A schematic phase diagram is shown in Fig. 10 illustrating this transition and its relationship to the evolution of the universe following the Big Bang. To explore this state, experiments have been carried out, first at the Bevalac at Berkeley, then at increasingly higher energies at the AGS in Brookhaven and the SPS at CERN, and soon at a new collider, the RHIC (Relativistic Heavy-Ion Collider) facility at Brookhaven that is to come into operation shortly. Since the confinement of quarks in hadrons is one of the key features of the strong-interaction world, this deconfinement, to a volume larger than that of a hadron, is of intense interest. A key question is how such deconfinement might be observed unambiguously.

Collisions between two heavy nuclei at ultrarelativistic energies produce many thousands of fragments. Their detection, identification, and characterization is a formidable experimental challenge. The first question is whether large densities in energy and baryon number are indeed obtained in such collisions—whether the kinetic energy is absorbed or, whether the two nuclei primarily just pass through each other. This may be deduced from the measurements of the transverse momentum carried by the products of the interaction. Such "stopping" studies at the AGS, at laboratory energies up to 14 GeV per nucleon show clearly that the kinetic energy is absorbed, and that high temperature and high baryon density are indeed created. This remains true in work at CERN up to laboratory energies of 200 GeV per nucleon. As yet, there is no unequivocal evidence in these data for a phase transition. The energies at RHIC will be an order of magnitude higher—and it is expected that this will lead to the formation of a high-temperature low baryon-density system well past the expected transition point.

How the properties of this transitory state of matter can be deduced from the data is the subject of intense discussions between experimenters and theorists. Some of the possible "signatures" discussed and explored in current experiments are the suppression of the production of J/ψ mesons due to screening of the charm-anticharm interaction by the surrounding quarks and gluons, an increase in energetic leptons in radiation from the early stages of the transitory state, the modification of the width and decay modes of specific mesons, such as the ρ and ϕ, enhancement in the production of strangeness, the attenuation of high energy jets, etc. A change in the state of matter should first show up in a clear correlation between a number of such signatures.

Another possibility at high energy density is that the intrinsic chiral symmetry of QCD may be restored. This would show up through modifications in the masses of mesons. Possibly, nonstatistical fluctuations in the distributions of pions might signal the production of a so-called "disoriented chiral condensate." The major point is not the specific scenarios in such a complex environment, but that these energy densities will bring an unprecedented new regime of matter under experimental scrutiny where our current pictures will necessarily have to undergo radical changes (Harris and Mueller, 1996).

VI. TESTS OF THE STANDARD MODEL

Most of the tests of the standard model of the strong and electroweak interactions at nuclear energies have involved semileptonic interactions, particularly electrons and nucleons, and rare decay modes, primarily of kaons. Here we describe some of the semileptonic tests.

A. Beta decay

The study of superallowed Fermi beta decays (parent nucleus of spin/parity $J^\pi = 0^+ \rightarrow$ daughter 0^+) in the same family of isospin (isospin multiplet) permit an important test of the standard model to be carried out via the unitarity of the matrix that describes the weak interaction connecting the various quarks: the Cabibbo-Kobayashi-Maskawa matrix (Towner and Hardy, 1995). The matrix element V_{ud} connecting up and down quarks is by far the largest one in the unitarity of

$$U \equiv |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1.$$

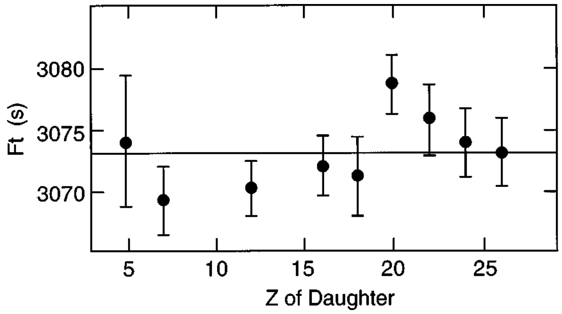

FIG. 11. Beta-decay transition probabilities (Ft values) for nine superallowed Fermi β-decays and the best least-squares one-parameter fit, plotted as a function of the proton number of the final nucleus (Towner and Hardy, 1995).

Here V_{us} and V_{ub} connect the up quark with the strange and bottom quarks, respectively. The precise measurements of superallowed transitions together with radiative corrections and removal of charge-dependent nuclear effects allow one to determine V_{ud} to better than 10^{-3}. In addition, these measurements, shown in Fig. 11, demonstrate that CVC (conserved vector current) holds to $\sim 4 \times 10^{-4}$. A straightforward analysis of the experiments, including a recent ^{10}C experiment, gives $V_{ud} = 0.9740 \pm 0.0006$. Together with the measurements of V_{us} and V_{ub}, one then obtains $U = 0.9972 \pm 0.0019$. There remain uncertainties, particularly in the charge-dependent nuclear effects; it has been proposed that these corrections can be approximated by a smooth Z dependence. In that case $U = 0.9980 \pm 0.0019$. However, better calculations of this charge dependence remain to be carried out.

B. Double beta decay

The decay $(A,Z) \rightarrow (A,Z+2) + e^- + e^- + \overline{\nu} + \overline{\nu}$ is expected in the standard model and has been seen in several nuclei (^{82}Se, ^{100}Mo, and ^{150}Nd) with half-lives of about 10^{20} y, consistent with the standard model (Moe and Vogel, 1994). Searches for the no-neutrino decay mode, important for determining whether ν's are massive and of the Majorana (neutrino and antineutrino are identical) type, are being continuously improved. The present lower limit on the half-life is 3×10^{24} y for ^{74}Ge.

C. Semileptonic parity-nonconservation studies

The surprising finding of strangeness in the nucleon led to considerable experimental and theoretical activity. Recently, in an ongoing experiment (SAMPLE) at MIT, the weak interaction is being used to investigate the contribution of strangeness to the proton's anomalous magnetic moment. As in all parity-violation experiments, it is the interference of weak with electromagnetic amplitudes that is sought in a parity-odd signal such as $\langle \vec{j} \rangle \cdot \vec{p}$, where $\vec{p}$ is the incident momentum of the electron and $\langle \vec{j} \rangle$ is its polarization. The presence of strangeness in the nucleon can modify the momentum

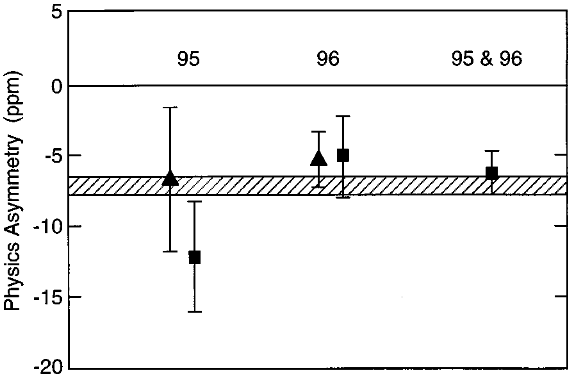

FIG. 12. Results for the parity-violating asymmetry measured in the SAMPLE experiment in the 1995 and 1996 running periods. The hatched region is the asymmetry band (due to axial radiative corrections) for $F_2^s = 0$.

dependence of the form factors, but it can also add two new unconstrained ones, a vector magnetic form factor and an axial (isoscalar) form factor. The results to date (Mueller *et al.*, 1997) are inconclusive, but do not indicate any strangeness (within large errors), as shown in Fig. 12. Further experiments are planned.

Other precision parity-violating (PV) studies of the weak interactions of electrons and nuclei have been carried out with atoms. Despite their being at lower momenta, where the PV effects are smaller, $\sim 10^{-11}$, these experiments have reached the incredible precision of 1/2% in the parity-violating asymmetry. At the present time theoretical errors are at the level of $\sim 1\%$. At this level of precision the atomic experiments provide meaningful tests of the standard model. The dominant weak-interaction term is $a_\mu V^\mu$ where a_μ is the axial current of the electron and V^μ is the hadronic vector current, which is coherent over the nucleus. The effective charge, the weak equivalent of the electrical charge in this case, is

$$Q_W = (1 - 4\sin^2\theta_W)Z - N, \tag{7}$$

where θ_W is the Weinberg angle, $\sin^2\theta_W \simeq 0.23$. Q_W is large for heavy atoms. The measurement on Cs, a one-valence-electron atom, at the 0.5% level, gives $Q_W = -72.35 \pm 0.27_{\rm exp} \pm 0.54_{\rm th}$ (Wood *et al.*, 1997). This limits deviations from the standard model.

The term $v_\mu A^\mu$, where v_μ is the weak vector current of the electron and A^μ is the nuclear axial current, is much smaller than $a_\mu V^\mu$ because for the electron $v^\mu \propto (1 - 4\sin^2\theta_W) \sim 0.1$ and only a single nucleon contributes to $A^\mu \propto \langle \vec{\sigma} \rangle$, the nuclear spin. Thus the asymmetry is reduced by $\geqslant 500$. The atomic measurements of this term make use of the hyperfine structure, which is due to the nuclear spin. This term has not yet been detected because it is hidden by the stronger nuclear "anapole" moment, a toroidal axial current of the nucleus coupling to photons. This is a weak parity-violating moment, which does not fit into the usual characterization of electromagnetic moments of nucleons. It is an effective axial vector coupling of the photon to the nucleus. The recent measurement in atomic Cs at the 1/2% level (Wood *et al.*, 1997) has discovered the nuclear anapole moment, the first anapole moment observed for such a microscopic system.

The experiment is of particular interest because it is sensitive to the weak internucleon force caused by neutral currents. This force has not been found in pure nuclear experiments and the upper limit found there (in ^{18}F) is at least a factor of three below that deduced from the anapole measurement, and also from a theoretical quark model. It remains to be seen whether this is an experimental or theoretical problem.

D. The nonleptonic weak interaction

The nonleptonic part of the weak interaction is of interest because it is the least well-understood one due to the strong interactions of all particles involved. The initial knowledge came from the weak decays of strange mesons and baryons. Even here, there remains the problem of fully understanding the ratio of parity-nonconserving to parity-conserving amplitudes in the decays of hyperons. Due to the change in flavor, only charged currents contribute to these decays in the electroweak theory. With the advent of precision nuclear experiments it became possible to study the weak interactions of nucleons by means of parity-violating asymmetries with polarized beams. These experiments do not probe the standard model as much as our understanding of the structure and weak forces of the nucleons. The asymmetry comes about from the interference of the weak and strong forces. Experiments in *pp* scattering and in light nuclei have provided the most reliable information (Adelberger and Haxton, 1985). The weak neutral currents have yet to be seen in nonleptonic weak interactions. They are the primary source of the isospin-changing $\Delta I = 1$ interaction, which arises from π exchange with one weak (f_π) and one strong pion coupling to nucleons. Since there is only an upper limit on the asymmetry in ^{18}F, which is determined by this mechanism, neutral-current effects have not yet appeared. Further measurements are planned for f_π, e.g., in low-energy polarized neutron capture by hydrogen, e.g., $n + p \rightarrow d + \gamma$.

E. Time-reversal invariance

Despite the finding of CP violation in 1964, over 30 years ago, we still do not have any definitive theory of time-reversal noninvariance. This is not due to a lack of effort. The only system where CP violation (and by implication T violation) has been found is in the K^0 and $\overline{K}^0$ system. To date, the most sensitive searches for time-reversal-invariance breaking are those for an atomic electric dipole moment of a neutron (Smith *et al.*, 1990; Alterev *et al.*, 1992) or atomic ^{199}Hg (Jacobs *et al.*, 1993; 1995); these tests are sensitive to simultaneous violations of parity and time-reversal invariance. No finite time-reversal violation effect has yet been published, but the upper limits keep decreasing and have already ruled out some models of CP violation.

VII. EXPERIMENTAL FACILITIES

The investigation of the properties of the nucleus has required the development of new tools with which to probe this realm of physics. These developments continue in a number of forms, an example is the new technologies based on superconductivity in both magnets and rf-accelerating structures. The pace of experimental exploration in nuclear physics is largely set by the rate at which the appropriate techniques become available.

While the early accelerators and other equipment were of relatively modest cost, and so could be duplicated at a number of university and other laboratories, the field has evolved in that latter part of the century, and it has increasingly required facilities that represent major investments. Though the scale of these has not been that of facilities in particle physics, it has required careful planning and priority choices, carried out primarily through the Nuclear Science Advisory Committee, with broad participation by the scientific community.

In the last two decades two major new facilities have emerged from this organized planning process (CEBAF and RHIC) along with a number of smaller ones. These will play a major role in determining the course of the science as we enter the next century.

VIII. OUTLOOK

The study of the structure of nuclei, of hadronic matter, started less than 100 years ago. Enormous advances have been made in this time. But much work remains. Even the simplest building blocks of hadronic matter that we have in our world, the proton and neutron, are structures that are incompletely understood. So are the interactions between them, the quantitative features of the forces that hold nuclei together. The properties of nuclei as observed experimentally are understood in the framework of approximate models, but the more fundamental reasons for the validity of many of these models are not well understood—nor can we reliably extrapolate these properties to extreme conditions, whether in the limits of stability, or the limiting energy densities of matter.

Concerted efforts of nuclear physicists, theorists, and experimentalists is needed to pursue these areas of knowledge into the 21st century.

ACKNOWLEDGMENTS

The authors would like to thank their colleagues G. Bertsch, D. Geesaman, W. Haxton, R. Janssens, G. Miller, and R. Wiringa for helpful discussions and advice in connection with the preparation of this article. This research was supported by the U.S. Department of Energy, Nuclear Physics Division, under Contract W-31-109-ENG-38 and Grant DE-FG06-90ER40561.

REFERENCES

Adami, C., and G.E. Brown, 1993, Phys. Rep. **224**, 1.

Adelberger, E.G., and W.C. Haxton, 1985, Annu. Rev. Nucl. Part. Sci. **35**, 501.

Alterev, I.S., *et al.*, 1992, Phys. Lett. B **276**, 242.

Arima, A., and F. Iachello, 1981, Annu. Rev. Nucl. Part. Sci. **32**, 75.

Ashman, J., *et al.*, 1989, Nucl. Phys. B **328**, 1.

Ashman, J., 1997, Phys. Rev. D **56**, 5330.

Baktash, C., B. Haas, and W. Nazarewicz, 1995, Annu. Rev. Nucl. Part. Sci. **45**, 543.

Baldsiefen, G., *et al.*, 1995, Nucl. Phys. A **587**, 562.

Bernstein, A.M., and B.R. Holstein, 1991, Comments Nucl. Part. Phys. **20**, 197.

Bernstein, A.M., and B.R. Holstein, 1995, Int. J. Mod. Phys. E **4**, 193.

Bethe, H.A., 1999, Rev. Mod. Phys. **71** (this issue).

Bohr, A., and B. Mottelson, 1969, *Nuclear Structure* (Benjamin, Inc., New York).

Bugg, D.V., 1985, Annu. Rev. Nucl. Part. Sci. **39**, 295.

Carlson, C.E., J.R. Hiller, and R.J. Holt, 1997, Annu. Rev. Nucl. Part. Sci. **47**, 395.

Carlson, J., and R. Schiavilla, 1998, Rev. Mod. Phys. **70**, 743.

Chrien, R., and C. Dover, 1989, Annu. Rev. Nucl. Part. Sci. **39**, 113.

Diamond, R.M., and F.S. Stephens, 1980, Annu. Rev. Nucl. Part. Sci. **30**, 85.

Dieperinck, A.E.L., and P.K.A. de Witt Huberts, 1990, Annu. Rev. Nucl. Part. Sci. **40**, 239.

Ericson, T., and W. Weise, 1988, *Pions and Nuclei* (Clarendon Press, Oxford).

Geesaman, D.F., K. Saito, and A.W. Thomas, 1995, Annu. Rev. Nucl. Part. Sci. **45**, 337.

Hansen, P.G., A.S. Jensen, and B. Jonson, 1995, Annu. Rev. Nucl. Part. Sci. **45**, 591.

Harris, J., and B. Mueller, 1996, Annu. Rev. Nucl. Part. Sci. **46**, 71.

Haxton, W.C., 1995, Annu. Rev. Astron. Astrophys. **33**, 459.

Hofmann, S., *et al.*, 1996, Z. Phys. A **354**, 229.

Holstein, B.R., 1995, "Chiral Perturbation Theory: a Primer," hep-ph/9510344 (unpublished).

Jacobs, J.P., *et al.*, 1993, Phys. Rev. Lett. **71**, 3782.

Jacobs, J.P., *et al.*. 1995, Phys. Rev. A **52**, 3521.

Janssens, R.V.F., and T.L. Khoo, 1991, Annu. Rev. Nucl. Part. Sci. **41**, 321.

Kaplan, D.B., M. Savage, and M. Wise, 1998, Phys. Lett. B **424**, 390.

Ko, C.M., G. Li, and V. Koch, 1997, Annu. Rev. Nucl. Part. Sci. **47**, 505.

Machleidt, R., 1989, in *Advances in Nuclear Physics*, Vol. 19, edited by J.W. Negele and E. Vogt (Plenum, New York), p. 189.

Meissner, Ulf G., Ed., 1992, *Effective Theories of the Standard Model* (World Scientific, Singapore).

Miller, G.A., 1994, Annu. Rev. Nucl. Part. Sci. **45**, 501.

Moe, M., and S.P. Vogel, 1994, Annu. Rev. Nucl. Part. Sci. **44**, 247.

Mueller, B., *et al.*, 1997, Phys. Rev. Lett. **78**, 3824.

Nolan, P.J., and P.J. Twin, 1988, Annu. Rev. Nucl. Part. Sci. **38**, 533.

Pandharipande, V.R., I. Sick, and P.K.A. de Witt Huberts, 1997, Rev. Mod. Phys. **69**, 981.

Smith, K.F., *et al.*, 1990, Phys. Lett. B **234**, 191.

Tanihata, I., 1995, Prog. Part. Nucl. Phys. **3**, 505.

Towner, I.S., and J.C. Hardy, 1995, in *Symmetries and Fundamental Interactions in Nuclei*, edited by W.C. Haxton and E.M. Henley (World Scientific, Singapore), p. 183.

Twin, P.J., *et al.*, 1986, Phys. Rev. Lett. **57**, 811.

Van Kolck, U., 1998, Sixth International Conference on Intersections of Particle and Nuclear Physics (AIP, New York), in press.

Weinberg, S., 1979, Physica A **96**, 327.

Wood, C.S., *et al.*, 1997, Science **275**, 1759.

Woods, P.J., and C.N. Davids, 1997, Annu. Rev. Nucl. Part. Sci. **47**, 541.