RESOURCE LETTER

Roger H. Stuewer, *Editor*
School of Physics and Astronomy, 116 Church Street SE,
University of Minnesota, Minneapolis, Minnesota 55455

This is one of a series of Resource Letters on different topics intended to guide college physicists, astronomers, and other scientists to some of the literature and other teaching aids that may help improve course content in specified fields. [The letter E after an item indicates elementary level or material of general interest to persons becoming informed in the field. The letter I, for intermediate level, indicates material of somewhat more specialized nature; and the letter A indicates rather specialized or advanced material.] No Resource Letter is meant to be exhaustive and complete; in time there may be more than one letter on some of the main subjects of interest. Comments on these materials as well as suggestions for future topics will be welcomed. Please send such communications to Professor Roger H. Stuewer, Editor, AAPT Resource Letters, School of Physics and Astronomy, University of Minnesota, 116 Church Street SE, Minneapolis, MN 55455; e-mail: rstuewer@physics.umn.edu.

Resource Letter FNP-1: Frontiers of nuclear physics

G. F. Bertsch[a)]
Department of Physics and Institute of Nuclear Theory, University of Washington, Box 351560 Seattle, Washington 98195

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This Resource Letter provides a bibliography of the current research activities in nuclear physics and also a guide for finding useful nuclear data. The major areas included are nuclear structure and reactions, symmetry tests, nuclear astrophysics, nuclear theory, high-density matter, and nuclear instrumentation.

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I. INTRODUCTION

In the past decades nuclear physics has become quite diverse, encompassing not only the properties of atomic nuclei that can be found in nature or produced in accelerators, but also the physics of hot dense matter formed in high-energy nuclear collisions and the physics of the subnucleonic degrees of freedom within the nucleon. For the purpose of this Resource Letter, I will not try to cover all of these areas but will restrict it to physics involving nucleons together. The traditional topics of nuclear physics concern nuclei in their ground states and in states at low excitation energy. Much research continues in this area, with emphasis shifting to nuclei at the limits of particle stability. Moving to the boundary with particle physics, nuclei are used to study high density matter (the putative ''quark-gluon plasma''), the effects of a nuclear environment on subnucleonic degrees of freedom, and fundamental symmetries of the strong interaction. The leading publications for the research literature are

Physical Review Letters (Nuclear physics section)
Physical Review C
Nuclear Physics A

Articles on specific topics can be found in the specialized review serials

Annual Review of Nuclear and Particle Science
Advances in Nuclear Physics (Plenum, New York)

Good reviews of nuclear subjects also can be found in the general physics serials

Physics Reports
Reports on Progress in Physics
Reviews of Modern Physics

The leading conference series in nuclear physics is the triennial International Conference on Nuclear Physics that began in Chicago in 1951. The 2001 meeting was in Berkeley, and the 2004 meeting is in Chalmers, Sweden.

1. **Nuclear Physics in the 21st Century: International Nuclear Physics Conference, INPC 2001, Berkeley, California, 30 July–3 August, 2001**, edited by E. B. Norman, L. S. Schroeder, and G. Wozniak, AIP Conference Proceedings, Vol. 610 (American Institute of Physics, Melville, NY, 2002). (A)

An overview of the frontier areas of nuclear physics is given in the report

2. **Nuclear Physics: The Core of Matter, the Fuel of Stars**, Committee on nuclear physics (National Academy, Washington, DC, 1999). (E)

For this bibliography, I will emphasize pedagogical review articles as much as possible. Some of the areas covered lack suitable reviews, and I cite the research literature.

II. BASIC NUCLEAR DATA

The core subject matter of nuclear physics is presented in a number of undergraduate textbooks. To be recommended for its compactness and availability is

3. **Particles and Nuclei, and Introduction to the Physical Concepts**, B. Povh, K. Rith, C. Scholz, and F. Zetsche (Springer, New York, 1995). (E)

Also in this section I list some sources of basic nuclear data that are still very useful in applications. Basic spectroscopy data for nuclei within a few units of the stability line are compiled in the two-volume set

4. **Table of Isotopes**, 8th ed., R. B. Firestone (Wiley, New York, 1996). This is a comprehensive compilation of energy level diagrams and

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[a)] Electronic mail: bertsch@u.washington.edu decay chains for mass numbers up to A=270. It also includes the ground properties of nuclei: spin, parity, magnetic moment, and quadrupole moment. Updates to the compilation are published separately; the most recent is 1999. (I)

More detailed data and data organized by properties of interest are published in

Nuclear Data Tables
Atomic Data and Nuclear Data Tables

The nucleon-nucleon interaction is characterized by the partial-wave phase shifts in nucleon-nucleon scattering and the properties of the bound state, the deuteron. See

5. "Partial-wave analysis of all nucleon-nucleon scattering data below 350 MeV," V. Stoks *et al*., Phys. Rev. C **48**, 792–815 (1993). This is the definitive analysis of the nucleon-nucleon interaction, analyzing the scattering data to determine the scattering phase shifts. Tables of the scattering phase shifts can be downloaded from the authors' web site at http://nn~online.sci.kun.nl/. Reference 6 is a companion article. (A)

6. "Construction of high-quality NN potential models," V. Stoks *et al*., Phys. Rev. **49**, 2950–2962 (1993), fits the phase shift information to models of the nucleon-nucleon interaction, called "Nijmegen potentials." (A)

Another set of potentials in common use are the Argonne parameterizations; see, for instance,

7. "Accurate nucleon-nucleon potential with charge-independence breaking," R. B. Wiringa, V. G. J. Stoks, and R. Schiavilla, Phys. Rev. C **51**, 38 (1995). (A)

The binding energy of a nucleus continues to be an important topic not only for the comprehensive understanding of nuclear physics, but also for weak-interaction studies and astrophysics. A compilation of the experimental binding energies is published from time to time by Audi and Wapstra, most recently as

8. "The 2003 atomic mass evaluation," G. Audi, A. H. Wapstra, and C. Thibault, Nucl. Phys. A **729**, 337–676 (2003). The tabulation here includes about 2500 nuclei. The data file for this tabulation is available at the website http://csnwww.in2p3.fr/AMDC/masstables/Ame2003/mass.mas03. (A)

Finally, nuclear sizes and their charge distributions may be needed for applications. These are compiled in the following two references.

9. "Nuclear charge-density-distribution parameters from elastic electron scattering," H. de Vries, C. W. de Jager, and C. de Vries, At. Data Nucl. Data Tables **36**, 495–536 (1987). This is a compilation of parameters fitting the nuclear charge distribution as determined by elastic electron scattering. More accurate values of the charge radii can be obtained by including data from muonic atoms. This has been done in the compilation, Ref. 10. (A)

10. "Systematics of nuclear charge radii," E. G. Nadjakov, K. P. Marinova, and Y. P. Gangrsky, At. Data Nucl. Data Tables **56**, 133–157 (1994). See also for neutron distributions Ref. 11 (A)

11. "Experimental methods for studying nuclear density distributions," C. J. Batty *et al*., Adv. Nucl. Phys. **19**, 1–188 (1989). (I)

III. STRUCTURE AND LOW-ENERGY PHYSICS

Nuclear structure continues to be an active area of research, made possible by accelerators of increasing luminosity for the production of rare isotopes, and by detectors of improved resolution and granularity. Nuclei in their ground and low-lying excited states are also used to test the fundamental symmetries of nature, and I include references to these studies in this section.

A. The borders of the chart of nuclides

A long-term effort in nuclear physics has been the extension of the table of nuclides beyond the heaviest known. This has been partly motivated by predictions of a new region of stability around element number 114. Nuclides well beyond uranium are produced by heavy-ion fusion reactions and are detected by their characteristic alpha-decay energies. As of 2003, nuclides going up to element number $Z=114$ have been produced and identified, but no isotopes heavy enough to reach the predicted island of stability have been reported. The searches and their results are presented in

12. "Making new elements," P. Armbruster and F. Hessberger, Sci. Am. **279**, 72–77 (1998). (E)

13. "The discovery of the heaviest elements," S. Hoffmann and G. Münzenberg, Rev. Mod. Phys. **72**, 733–768 (2000). At the time this review was written, there was also a claim for element 118 which proved to be incorrect. (I)

Another major thrust in current research concerns the properties of nuclei very far from the beta-stability line. With present-day facilities, nuclei can be produced on the neutron rich side right up to the border of particle stability (the "neutron drip-line") for light nuclei ($Z\leqslant 20$). One fruitful experimental technique to make and study exotic neutron-rich nuclei is to produce them by fragmenting heavy nuclei in ion beams, and then measure their properties by the reactions they undergo on secondary targets. Two reviews of this subject are

14. "Physics with radioactive nuclear beams," R. N. Boyd and I. Tanihata, Phys. Today **45**(6), 44–52 (1992). (E)

15. "Direct reactions with exotic nuclei," P. G. Hansen and J. A. Tostevin, Annu. Rev. Nucl. Part. Sci. **53**, 219 (2003). (A)

An important finding is that nuclides near the neutron drip line have distinctive properties associated with the "halo" of the nearly unbound neutrons. A much-studied example is ^{11}Li, bound by only 300 keV with respect to neutron emission. It is "Borromean" as well as a halo nucleus, meaning that when a neutron is removed a second neutron becomes unbound as well. See Ref. 16.

16. "Halo nuclei," S. M. Austin and G. F. Bertsch, Sci. Am. **272**, 90–95 (1995). (E)

On the proton-rich side, even particle-unbound nuclei can be studied in laboratory targets because their proton decays are inhibited by the Coulomb barrier. One can measure properties of nuclei along the $N=Z$ line (equal neutron and proton numbers) up to about $Z=50$. The spectroscopy on this edge of the nuclear chart is reviewed in

17. "Nuclei beyond the proton drip-line," P. J. Woods and C. N. Davids, Annu. Rev. Nucl. Part. Sci. **47**, 541–590 (1997). (I)

One of the fundamental measurements associated with the exploration of the nuclei far from the stability line is the nuclear binding energy. Alongside the compilation mentioned above (Ref. 8), there are many models to describe the binding-energy systematics. The first was the famous five-parameter Weizsäcker formula proposed in the mid-1930s, which describes data to an accuracy of 3 MeV (rms error). Present-day systematic models have 25–35 parameters and achieved an accuracy of 0.6–0.7 MeV. The topic of nuclear masses and their theory was reviewed in 2003 by

18. "Recent trends in the determination of nuclear masses," D. Lunney, J.

M. Pearson, and C. Thibault, Rev. Mod. Phys. **75**, 1021–1083 (2003). (I)

With the exploration of nuclei far from stability, the possible existence of new magic numbers has been given much attention. In the last decade properties of new doubly-magic nuclei such as ${}^{132}_{82}\mathrm{Sn}_{50}$ have been measured. See Ref. 69 which discusses the search for new, lighter magic nuclei from a theoretical point of view.

B. Spectroscopy

An important thrust in nuclear spectroscopy in recent years has been the study of states of high angular momentum. Using heavy-ion fusion reactions, nuclear states of angular momentum up to $J=50-60$ can be observed, as is described for example in the experimental measurement

19. "Competition between terminating and collective structures above spin $40\hbar$ in ^{154}Dy," W. C. Ma *et al.*, Phys. Rev C **65**, 034312 (2002). (A)

At high angular momentum, nuclei may undergo a shape transition to a highly deformed state, called "superdeformed." The rotational band associated with the deformation may be observed by the gamma decay chain, exciting the nucleus by a heavy-ion reaction. An early review of the spectroscopy of these superdeformed states is

20. "Superdeformed nuclei," R. V. F. Janssens and T. L. Khoo, Annu. Rev. Nucl. Part. Sci. **41**, 321–355 (1991) (A)

Since this review, the superdeformed bands have been placed within the spectroscopy of the ordinary states by identifying the cross-over transitions. A recent example is in the nucleus ^{152}Dy, where superdeformation was first observed.

21. "Direct decay from the superdeformed band to the yrast line in ^{152}Dy," T. Lauritsen *et al.*, Phys. Rev. Lett. **88**, 042501 (2002). (A)

A completely different kind of band was discovered in the mid-1990s, one that is apparently not directly associated with nuclear shape. The distinguishing feature is an in-band decay by magnetic-dipole radiation instead of the predominant quadrupole decay of ordinary deformed bands. This behavior is discussed in the article

22. "Spontaneous symmetry breaking in rotating nuclei," S. Frauendorf, Rev. Mod. Phys. **73**, 463–514 (2001). This review is mainly theoretical, but it includes a discussion of the phenomenology of the magnetic bands. (A)

C. Hypernuclear physics

Nuclei with a nonzero strangeness are produced by reactions involving hyperons such as the Λ particle or the K meson. For a general review, see

23. "Strangeness nuclear physics," A. Gal, Nucl. Phys. A **670**, 229 (2000). (A)

Much information about the spectroscopy of Λ-hypernuclei (shells, binding potential, etc.) has been obtained from the reaction $A+\pi\rightarrow K^{+}+A_{\Lambda}$, for example measured in

24. "Spectroscopic study of ${}^{10}_{\lambda}$B,...,${}^{208}_{\Lambda}$Pb by the (π^{+},K^{+}) reaction," T. Hasegawa *et al.*, Phys. Rev. C **53**, 1210–1220 (1996). (A)

The interaction of K^{-} mesons with nuclei is of special interest because it is strongly attractive, with possible consequences for dense matter (see Refs. 79–81). Optical potentials derived from data on kaonic atoms are given in

25. "Strong interaction physics from hadronic atoms," C. J. Batty, E. Friedman, and A. Gal, Phys. Rep. **287**, 385 (1997). (A)

D. Symmetry tests and the Standard Model

The following monograph discusses the application of nuclear physics to test the Standard Model of the electroweak interactions and the violation of P and CP, and T symmetries:

26. Weak Interactions in Nuclei, B. R. Holstein (Princeton Univ. P., Princeton, 1989). (I)

Nuclear measurements have been important in testing the unitary of the Cabibo–Kobayashi–Maskawa matrix, one of the tenets of the Standard Model. The present status of the measurements of $u-d$ element of the matrix is given by

27. "Superallowed $0^{+}\rightarrow 0^{+}$ beta decay and CKM unitary," J. C. Hardy and I. S. Towner, Eur. Phys. J. A **15**, 223–227 (2002). According to these authors, the experimental values are inconsistent with unitarity (at the two-standard deviation level). (A)

28. "Is the unitarity of the quark-mixing CKM matrix violated in neutron beta-decay?" H. Abele *et al.*, Phys. Rev. Lett. **88**, 211801 (2002). This neutron decay experiment approaches the accuracy of the nuclear-decay measurements. (A)

The electroweak current induces a parity-violating component to the nucleon-nucleon interaction. This has been studied both in nucleon-nucleon scattering and in its effects on nuclear properties. See

29. "Parity-non-conservation in nuclear forces at low energy: phenomenology and questions," B. Desplanques, Phys. Rep. **297**, 1–61 (1998). This comprehensive review covers the older data on gamma transitions between nuclear levels as well at the experiments in the 1990s on low-energy neutron scattering from heavy nuclei. It also interprets the various kinds of data with a phenomenological potential-field model. (A)

30. "Parity violation in proton-proton scattering at 221 MeV," A. R. Berdoz *et al.*, Phys. Rev. Lett. **87**, 272301 (2001). This is recent measurement of parity violation in nucleon scattering, observing effects at higher energy than previously studied. (A)

31. "Parity violation in compound nuclei: experimental methods and recent results," G. E. Mitchell *et al.*, Phys. Rep. **354**, 157–243 (2001). This describes experiments observing parity violation in the scattering of low-energy neutrons on heavy nuclei, measuring the interference between *p*-wave resonances and *s*-wave background scattering. (A)

The weak neutral current also gives rise to parity violation in the interaction between electrons and nuclei. Electron-scattering experiments measuring the effects of the neutral current are reviewed by

32. "Parity-violating electron scattering and nucleon structure," D. H. Beck and R. D. McKeown, Annu. Rev. Nucl. Part. Sci. **51**, 189–217 (2001). (A)

In the domain of atomic spectroscopy, precise measurements have been made revealing the spin dependence of the parity-violating interaction, called the "anapole moment." See

33. "Atomic parity nonconservation and nuclear anapole moments," W. C. Haxton and C. E. Wieman, Annu. Rev. Nucl. Part. Sci. **51**, 261–293 (2001). (A)

The origin of the CP violation seen in meson decays is still uncertain. Theoretically there is also an accompanying violation of time reversal symmetry, which would give rise to a static dipole moment in atoms and nuclei. See

34. CP Violation Without Strangeness: Electric Dipole Moments of Particles, Atoms, and Molecules, I. Khriplovich and S. Lamoreaux (Springer-Verlag, Berlin, 1997). (I)

The current status of these tests of T violation is presented in

35. "The search for a permanent electric dipole moment," N. Fortson, P. Sandars, and S. Barr, Phys. Today **57**(6), 33–38 (2003). This artice is written for a general physics audience and includes a bibliography of recent measurements. (E)

For a recent development on the side of nuclear theory, see

36. "Nuclear octupole correlations and the enhancement of atomic time-reversal violation," J. Engel, J. L. Friar, and A. C. Hayes, Phys. Rev. C **61**, 035502 (2000). (A)

Since the discovery of neutrino oscillations in 1999, it is known that neutrinos have mass, permitting the double-beta decay of nuclei by emitting two electrons without any accompanying neutrinos. There is indirect evidence for double-beta decay from geochemical studies. However, that evidence does not distinguish between ordinary decay and neutrinoless decay. There is considerable effort underway now to make a direct observation. See

37. "The future of double beta decay research," Y. Zdesenko, Rev. Mod. Phys. **74**, 663–684 (2002). (I)

IV. REACTIONS

Here I cite research concerned with nuclear reactions at energies and momenta where the nucleons maintain their identity. High-energy reactions carried out to reveal sub-nucleonic structure appear in Secs. VI B and C.

A. Nuclear response

The response of nuclei to weak external fields or probes exhibits a variety of phenomena depending on the probe and the energy and momentum transfer. The low-energy response is often dominated by giant resonances, the collective excitations of the nucleus involving many nucleons excited coherently. For a general overview, see the proceedings of the 2003 conference on this topic, held in Paris:

38. Collective Excitations of Nuclei at Extremes, Nucl. Phys. A **731**, 3–430 (2004). (A)

Among the giant resonances, the most familiar is the giant dipole resonance, known from the early days of nuclear physics and last reviewed in 1975:

39. "Measurements of the giant dipole resonance with monoenergetic photons," B. L. Berman and S. C. Fultz, Rev. Mod. Phys. **47**, 713–761 (1975). (A)

Since then many more modes have been identified. Particularly noteworthy are the giant monopole, quadrupole, and Gamow–Teller resonances. The giant monopole is of special interest because its frequency is related to the compressibility of nuclear matter. It had been difficult to observe with great clarity because of the nearby quadrupole resonance, but improvements in accelerators now permit its accurate measurement by inelastic α-particle scattering; see, for instance,

40. "Isoscalar giant dipole resonance in ^{90}Zr, ^{116}Sn, and ^{208}Pb," H. L. Clark, Y. W. Lui, and D. H. Youngblood, Phys. Rev. C **63**, 031301 (2001). (A)

Measurements such as these can only be interpreted quantitatively with a model for the propagation of the perturbing particle in the nucleus. The optical model has served this role for many years; see

41. "Local and global nucleon optical models from 1 keV to 200 MeV," A. J. Koning and J. P. Delaroche, Nucl. Phys. A **713**, 231–310 (2003). Here are presented phenomenological optical potentials covering a wide range of nuclei. (A)

Nuclear excitations involving the spin degrees of freedom also exhibit some collectivity. See

42. "Probing the nuclear magnetic dipole response with electrons, photons, and hadrons," A. Richter, Prog. Part. Nucl. Phys. **34**, 261–284 (1995). Measurements using electron scattering at 180° have been particularly useful in locating collective magnetic-dipole strength. The observed concentration of strength in deformed nuclei has been interpreted as a collective "scissors mode." (A)

43. "The nuclear spin response to intermediate energy protons and deuterons at low momentum transfer," F. T. Baker *et al*., Phys. Rep. **289**, 235 (1997). This includes the nucleon charge-exchange reactions that have been very useful to observe the Gamow-Teller resonance. The response in the spin-isospin channel is also of interest for understanding the weak-current interactions with nuclei, for example, for neutrino scattering. (A)

44. "Distribution of the Gamow-Teller in ^{90}Nb and ^{208}Bi," A. Krasznahorkay *et al*., Phys. Rev. C **64**, 067302 (2001). This reports measurements using the (^{3}He,t) charge exchange reaction. (A)

45. "Charged-current neutrino-^{208}Pb reactions," C. Volpe, N. Auerbach, G. Colò, and N. Van Giai, Phys. Rev. C **65**, 044603 (2002). The response to the weak current is of interest for modeling astrophysical processes and for interpreting signals from neutrino detectors, motivating this theoretical paper. (A)

B. Electron scattering

As mentioned above (Ref. 9), elastic electron scattering has served as a high-precision probe of the nuclear-charge distribution. Inelastic electron scattering at low momentum transfer also has been valuable for the understanding of collective excitations in the nuclear response. At moderate momentum transfer one observes quasielastic scattering, peaked at energies corresponding to the recoil of free nucleons. A more recent focus has been high momentum transfer, where the cross sections are dominated by correlations and sub-nucleonic degrees of freedom. References for the latter are in Sec. VI A, "Quarks in nuclei." An example of a high-momentum measurement in the nucleonic domain is

46. "Inclusive electron-nucleus scattering at large momentum transfer," J. Arrington *et al*., Phys. Rev. Lett. **82**, 2056 (1999). Here the data can be described by spectral functions, called "y-scaling" functions, similar in spirit to the parton-distribution functions in phenomenological high-energy physics. (A)

The integral over all momentum transfers can be related to the charge correlations in the nucleus. Separating the response into longitudinal and transverse parts, the former directly probes this correlation function. Early measurements gave unsatisfactory results inconsistent with a sum rule for the charge, but it now appears that a proper analysis of the data gives a result consistent with the Coulomb sum rule. See

47. "Quasi-elastic response functions. The Coulomb sum revisited," J. Jourdan, Nucl. Phys. A **603**, 117 (1996). This short article contains citations on the experimental measurements of electron scattering in the quasi-elastic domain, carried out in the early 1980s. Unfortunately, the accuracy of the data does not yet permit one to extract information about the short-range correlation between charges. (A)

There is a corresponding sum for the transverse response, which has contributions from many-body exchange currents as well as the charges themselves. This sum is significantly higher than the Coulomb sum, and the excess seems to be accounted for by mesonic effects contributing to the exchange currents. See

48. "Longitudinal and transverse quasielastic response functions of light nuclei," J. Carlson, J. Jourdan, R. Schiavilla, and I. Sick, Phys. Rev. C **65**, 024002 (2002). (A)

C. Low-energy heavy-ion reactions

Fusion reactions between nuclei are dominated by the Coulomb barrier, below which the cross sections become very small. There has been much experimental study of the below-barrier fusion. Most simply, the cross sections are interpreted as a one-dimensional quantum-mechanical barrier penetration, but the many-particle degrees of freedom can play a significant role. This topic reviewed in

49. "Measuring barriers to fusion," M. Dasgupta, D. J. Hinde, N. Rowley, and A. M. Stefanini, Annu. Rev. Nucl. Part. Sci. **48**, 401–461 (1998). (I)

In 2002, sharp deviations from the barrier penetration formula were found at energies far below the barrier. See, for example,

50. "Unexpected behavior of heavy-ion fusion cross sections at extreme subbarrier energies," C. L. Jiang *et al.*, Phys. Rev. Lett. **89**, 052701 (2002). The deviations found here are as yet unexplained. (A)

There are many other phenomena observed in heavy-ion reactions, ranging from rainbow physics in elastic scattering to spectroscopic enhancements of inelastic cross sections associated with deformations, pairing, and other collective degrees of freedom. The theory of these reactions, with some experimental examples, is presented in the texts:

51. **Semi-classical Methods in Nucleus-nucleus Scattering**, D. M. Brink (Cambridge U.P., New York, 1985). (I)
52. **Heavy Ion Reactions**, R. A. Broglia and A. Winther (Addison–Wesley, Redwood City, 1991). (A)

Going up in excitation energy beyond the spectroscopic region of discrete levels, one comes to a domain where the nuclei produced in the reaction have time to equilibrate and are best described with statistical concepts. One can ascribe to such nuclei a temperature, which is directly measurable in its decay properties. An example in which the decays are used to extract statistical properties is

53. "Investigation of the level density parameter using evaporative α-particle from the ^{19}F+^{181}Ta reaction," A. L. Caraley, B. P. Henry, J. P. Lestone, and R. Vandenbosch, Phys. Rev. C **62**, 054612 (2000). (A)

At higher energies nuclei decay before they have time to fully equilibrate. Nevertheless, the composition and kinetic energies of the cluster emission can still be described in statistical terms up to temperatures of the order of 5 MeV. At the corresponding excitation energies, one sees dynamics of a hot expanding system of particles transforming from a condensed phase to a vapor phase. The expansion can take place with the simultaneous emission of many light nuclei, called multifragmentation. See

54. "Liquid-gas phase transition in nuclear multifragmentation," S. Das Gupta, A. Z. Mekjian, and M. B. Tsang, Adv. Nucl. Phys. **26**, 89–166 (2001). This is a comprehensive review covering both theory and the observations. (I)
55. "Evidence for spinodal decomposition in nuclear multifragmentation," B. Borderie *et al.*, Phys. Rev. Lett. **86**, 3252–3255 (2001). This is an example of an experiment showing multifragmentation. (A)
56. "Isotopic scaling in nuclear reactions," M. B. Tsang *et al.*, Phys. Rev. Lett. **86**, 5023–5026 (2001). These authors find new systematic trends in the production of light nuclei. (A)

The fragmentation of a nucleus by a high-energy proton, called spallation, has seen renewed interest as a source of exotic isotopes as well as for applications of nuclear physics (see Sec. VII B). An example of a recent study is

57. "Fission-residues produced in the spallation reaction U-238+p at 1 A GeV," M. Bernas *et al.*, Nucl. Phys. A **725**, 213–253 (2003). (A)

D. Astrophysical issues

While most stars are powered by nuclear fusion reactions, present-day issues on the interface of astrophysics and nuclear physics concern more exotic environments. One subject receiving much attention is the question of how elements heavier than iron are formed. From the abundances of the heavier elements it is clear that there is a slow process, which could come from neutron captures in an ordinary star, and a rapid process, which requires a very high neutron flux on a time scale of minutes. Candidates for this so-called "r-process" synthesis are the explosions of type-II supernova, the accretion disks of newly formed black holes, and the fusion of neutron stars in a binary system. Other issues related to the structure of neutron stars are discussed in the theory section, Sec. V E below. See also the web site of the Joint Institute for Nuclear Astrophysics (http://www.jinaweb.org/) for references in this field.

58. "The evolution and explosion of massive stars," S. E. Woosley, A. Heger, and T. A. Weaver, Rev. Mod. Phys. **74**, 1015–1071 (2002). (I)
59. "Nuclear reactions and stellar processes," K. Langanke and M. Wiescher, Rep. Prog. Phys. **64**, 1657–1701 (2001). (A)

V. NUCLEAR THEORY

The leading textbook on nuclear theory from the perspective of nonrelativistic quantum many-body theory is

60. **The Nuclear Many-Body Problem**, P. Ring and P. Schuck (Springer, New York, 1980). Unfortunately, this book is now out of print. (I)

Quite disparate theoretical methods are employed in calculating nuclear properties, depending on the size of the nucleus and the property under study.

A. The lightest nuclei

The lightest nuclei can be treated by calculating the full many-particle wave function with a Hamiltonian whose interaction fits the nucleon-nucleon scattering data, e.g., the interaction of Ref. 6. The binding energies of the triton (^{3}H) and ^{3}He have been studied intensively using two-nucleon potentials that are accurately fitted to the scattering phase shifts. Various computational methods have been applied including the Fadeev equations, the hyperspherical harmonic representation, and the Green's function Monte Carlo method. A summary of the different methods is presented in the review

61. "Structure and dynamics of few-nucleon systems," J. Carlson and R. Schiavilla, Rev. Mod. Phys. **70**, 743–842 (1998) (I).

All methods of calculating the three-nucleon binding energy converge on similar values, differing from the experimental binding energy by about 1 MeV. This demonstrates the evolution of the calculational techniques to a point where the numerical approximations are of secondary importance. Among the different calculational techniques, the Fadeev method is most flexible with respect to the parametrization of the interaction. In the article below, the authors used that method to assess the dependence of the calculated binding energy on the choice of interaction. The authors found very little variation among the local interactions, but a significant change when a nonlocal interaction is used.

62. "Triton binding energies for modern NN forces...," A. Nogga *et al*., Phys. Lett. B **409**, 19 (1997). The sizable discrepancy compared to the experimental binding energy shows convincingly the necessity of introducing three-body forces or subnucleonic degrees of freedom into the theory. It also should be mentioned that the dependence of nucleon-deuteron scattering is not reproduced by the fitted two-nucleon interaction. See Ref. 63. (A)

63. "N-d elastic scattering as a tool to probe properties of 3N forces," H. Witala *et al*., Phys. Rev. C **63**, 024007 (2001). (A)

The above-mentioned calculational techniques are also applicable to the four-body system, the α particle. A comparison of methods as implemented by different groups is reported in

64. "Benchmark test calculation of a four-nucleon bound state," H. Kamada *et al*., Phys. Rev. C **64**, 044001 (2001). Here the bindings were compared using a local interaction that fits the two-body scattering. The apparent numerical accuracy is about 0.1 MeV, and the theoretical binding is several MeV away from the experimental. (A)

Three-body forces have been added to the interaction and applied to nuclei up mass 10 or so using the variational Monte Carlo and Green's function Monte Carlo methods. It is found that the three-body term needed to fit mass 3 is also adequate to obtain a close value for the α-particle binding. The mass-5 system is not bound and exists only as a resonance in nucleon-α scattering, but one sees there that the nuclear spin-orbit interaction cannot be reproduced by the two-particle interaction alone. Thus, there must be added a spin-dependent three-body interaction as well. The calculations by the Monte Carlo method were summarized in the conference talk

65. "Quantum Monte Carlo calculations for light nuclei," R. B. Wiringa, Nucl. Phys. A **631**, 70c (1998). (A)

The properties of halo nuclei are often treated as a few-body system consisting of the halo nucleons interacting with each other and with a core treated as a particle. For example, the theory of ^{11}Li is treated as a three-particle system in

66. "Pair correlations near the neutron drip line," G. F. Bertsch and H. Esbensen, Ann. Phys. (NY) **209**, 327–363 (1991). (A)

Recently, a theoretical technique developed for relativistic quantum field theory has been applied with considerable success to the one- and two-nucleon sector of nuclear physics. In its simplest versions, the leading-order theory, it provides analytic formulas for observables containing parameters deduced from other measurements. A recent review is

67. "Effective field theory for few-nucleon systems," P. F. Bedaque and U. van Kolck, Annu. Rev. Nucl. Part. Sci. **52**, 339–396 (2002). The techniques are described in considerable detail along with many successful applications. However, there remain unresolved problems in dealing with the nuclear tensor interaction and with applications to the many-body sector. (A)

B. Shell model

For nuclei larger than mass 10 or so, it is not possible to treat the full many-particle wave function to sufficient accuracy to use the realistic nucleon-nucleon interactions. The most successful methods for heavier nuclei are based on the shell-model representation or, more generally, a representation based on the orbitals of a self-consistent mean field. The shell model with configuration interaction is the method of choice for many spectroscopy properties, in regions of nuclides where the valence spaces are not prohibitively large. A general reference is the book

68. The Nuclear Shell Model, K. Heyde (Springer, Berlin, 1991). (I)

One of the early successes of the shell model was its application to the spectroscopy of p-shell nuclei. This success was extended to the sd-shell by the next generation of computers, but heavier nuclei tax the presently available computer resources, as well as require many more parameters to define the interaction. Among the computer codes for shell model calculations in large spaces, the Oxbash code is well documented and freely available. It can be downloaded from the web sites ftp://ftp.nsc1.msu.edu/pub/oxbash/. Examples of recent applications are discussed in

69. "Frontier of shell model calculations," E. Caurier and G. Martinez-Pinedo, Nucl. Phys. A **704**, 60c–68c (2002). (A)

70. "The nuclear shell model towards the drip line," B. A. Brown, Prog. Part. Nucl. Phys. **47**, 517 (2001). (A)

Shell-model spaces larger than the limits imposed by the explicit diagonalization methods can sometimes be treated with the auxiliary-field Monte Carlo method. See

71. "Shell model Monte Carlo methods," S. E. Koonin, D. J. Dean, and K. Langanke, Phys. Rep. **278**, 1 (1997). This is an exposition of the method including many computational details. (A)

72. "Total and parity-projected level densities of iron-region nuclei in the auxiliary fields Monte Carlo shell model," H. Nakada and Y. Alhassid, Phys. Rev. Lett. **79**, 2939–2942 (1997). This is an example of an application well beyond the scope of diagonalization methods. (A)

C. Density-functional theory

The practicality of the shell-model methods depend strongly on the specific shell structure of the nuclei under consideration. In contrast, a more universally applicable theory can be made by treating the many-particle wave function as a product of independent orbitals, as in the Kohn–Sham theory of condensed matter. Nuclear energy-density functionals have been proposed since the 1960s, but it is only recently that the computational power has been available to make accurate calculations, particularly of deformed nuclei. See

73. "Self-consistent mean-field models for nuclear structure," M. Bender, P.-H. Heenen, and P.-G. Reinhard, Rev. Mod. Phys. **75**, 121–180 (2003). This comprehensive review discusses several kinds of functionals that have been applied. They are nonrelativistic theories having only contact interactions, nonrelativistic theory with finite-range interactions, and relativistic mean-field theory. As of 2003, only the nonrelativistic theories have been systematically applied over a large range of nuclei. (I)

74. "Pairing interaction and self-consistent densities in neutron-rich nuclei," J. Dobaczewski, W. Nazarewicz, and P. G. Reinhard, Nucl. Phys.

A **693**, 361–373 (2001). This article from the research literature addresses the interesting question of pairing effects in drip-line nuclei. (A)

D. Nuclear matter

Uniform matter with arbitrary densities of neutron and protons but no Coulomb interactions is a theorist's invention, but a very useful one for testing theories of the nuclear interaction as well as for treating physical problems involving a large number of nucleons. At a quantitative level, the uncertainty in the three-nucleon interaction that plagues the theory of light nuclei is also evident in nuclear matter theory. Nevertheless, a reasonable account can be given with fairly mild assumptions about the subnucleonic degrees of freedom. See, for example,

75. "Brueckner theory of nuclear matter with non-nucleonic degrees of freedom and relativity," R. Machleidt, Int. J. Mod. Phys. B **15**, 1535 (2001). (A)

76. "Equation of state of nucleon matter and neutron star structure," A. Akmal, V. R. Pandharipande, and D. G. Ravenhall, Phys. Rev. C **58**, 1084–1828 (1998). These authors calculate an equation of state based on empirical nucleon-nucleon interactions without subnucleonic degrees of freedom. (A)

The compressibility coefficient of nuclear matter can be estimated by the resonance frequency of the giant monopole, as was mentioned in Sec. IV A. Another way is to analyze the flow of nucleons in energetic heavy-ion collisions. This requires simulations of the collisions in the multifragmentation domain, which is done by using the Boltzmann equation including mean-field dynamics and Pauli blocking effects on the collisions.

77. "A guide to microscopic models for intermediate energy heavy-ion collisions," G. F. Bertsch and S. Das Gupta, Phys. Rep. **160**, 189–233 (1988). This review describes in detail the computational technique used in nuclear physics to solve the Boltzmann equation. (I)

78. "Isolation of the nuclear compressibility with the balance energy," D. G. Magestro, W. Bauer, and G. D. Westfall, Phys. Rev. C **62**, 041603 (2000). Here is an analysis of data extracting the compressibility of nuclear matter. (A)

E. Neutron-star structure

Another subject of current interest is the structure of neutron stars. Several observational properties depend on the nuclear matter equation of state and its transport properties. See

79. "Neutron star structure and the equation of state," J. M. Lattimer and M. Prakash, Astrophys. J. **550**, 426–442 (2001). This article investigates the consequences for various equations of state on the masses, radii, and moments of inertia of neutron stars. (A)

At the high densities in the core of the neutron stars, quark degrees of freedom (strange quarks in particular) may be important to the equation of state. From a hadronic point of view, the neutron matter can become hyperonic matter or can undergo kaon condensation. From a quark point of view, more exotic forms of matter such as a color-superconducting quark superfluid are under discussion.

80. "Phases of dense matter in neutron stars," H. Heiselberg and M. Hjorth-Jensen, Phys. Rep. **328**, 237–327 (2000). This article provides references to the various speculations about the form of the high density matter, ranging from nucleonic models to the quark liquid. (I)

81. "Dense quark matter in nature," M. Alford, arXiv:nucl-th/0312007 (2003). This preprint discusses the consequences of color superconductivity for neutron star masses. (A)

The neutron-star crust has special features of interest; the observed "glitches" show that it is partly decoupled from the rotating core. The nuclei embedded deep in the crust have very large neutron excesses and may assume rod or plate-like shapes, according to theoretical modeling:

82. "Neutron star crusts," C. P. Lorenz, D. G. Ravenhall, and C. J. Pethick, Phys. Rev. Lett. **70**, 379–382 (1993). (A)

VI. HIGH ENERGY NUCLEAR PHYSICS

A. Quarks in nuclei

One has a good qualitative understanding of the subnucleonic structure of nucleons based on QCD, but the consequences for nuclear properties show up mainly in the high-momentum response. One well-known effect is shadowing, the decrease of cross section on nuclear targets even for probes such as high-energy photons that naively would suffer nominal absorption in traversing the nucleus. See

83. "The hadronic properties of the photon in high-energy interactions," T. H. Bauer, R. D. Spital, and D. R. Yennie, Rev. Mod. Phys. **50**, 261–436 (1978). (A)

The response to high-energy inelastic electron scattering exhibits a more complex behavior, known as the "EMC effect." It is a prominent deviation of the response from independent nucleon behavior in a particular kinematic region, "small x," characterized by a large energy transfer compared to the nucleon mass and four-momentum transfer. At the smallest values of x the shadowing is prominent, but at slightly higher values there is an enhancement in the response. This has been studied intensively both experimentally and theoretically. A comprehensive review of this topic is given by

84. "The EMC effect," P. R. Norton, Rep. Prog. Phys. **66**, 1253–1297 (2003). (A)

The converse of the shadowing of electroweak probes would be an enhanced transparency of hadronic probes. This has been discussed for a long time in the context of QCD ("color transparency"). Clear experimental evidence has been difficult to find, but see below for a recent claim to observe the effect.

85. "Q^2 Dependence of nuclear transparency for exclusive ρ_0 production," A. Airapetian *et al.*, Phys. Rev. Lett. **90**, 052501 (2003). (A)

B. High-density matter

To study matter at the highest energy densities achievable in the laboratory, one observes collisions between nuclei produced by high-energy heavy-ion accelerators. In the 1990s the most powerful accelerator of this type was the SPS at CERN; now the spotlight has shifted to the RHIC at Brookhaven. In the next decade an even higher energy accelerator at CERN, the LHC, will be operational. The theoretical paradigm for describing high-density matter is QCD, which predicts a phase transition at high energy density from a gas of hadrons to a quark-gluon plasma. The overarching goal of the experimental effort is to identify the phase transition and observe the properties of the plasma phase. The researchers engaged in this quest have a biennial meeting,

Table I. Major accelerator facilities for nuclear physics research. This does not include the smaller accelerators where much of the research on nuclear structure and reactions is carried out.

Name	Location	Home Page
RHIC: Relativistic Heavy Ion Collider	Brookhaven	www.bnl.gov/RHIC/
ISOLDE: Large scale facility at CERN	Geneva	isolde.web.cern.ch/ISOLDE/
GANIL: Grand Accelerateur National d'Ions Lourdes	Caen	www.ganil.fr
GSI: Gesellschaft für Schwerionenforschung	Darmstadt	www.gsi.de/
NSCL: National Superconducting Cyclotron Laborary	East Lansing	www.nscl.msu.edu
CEBAF: Continuous Electron Beam Accelerator Facility	Newport News	www.jlab.org

"Quark Matter," where the latest progress on theory and experiment is presented. The most recent meetings were

86. 16th International Conference on Ultra-Relativistic Collisions, H. Gutbrod, J. Aichelin, and K. Werner, Nucl. Phys. **715**, 3–930 (2003). This reports on the 2002 Quark Matter meeting. (A)

87. 15th International Conference on Ultra-Relativistic Collisions, T. Hallman *et al*., Nucl. Physi. **698**, 3–707 (2002). This meeting reported the first results from the RHIC accelerator. (A)

At the most elemental level, the experiments look for characteristics of the particle distributions produced by the nucleus-nucleus collisions that are different from the distributions in nucleon-nucleon reactions at the same energy. Particularly sought are effects that would depend on the QCD structure of the dense matter within the collision region. For a nontechnical overview, see

88. "What have we learned from the relativistic heavy ion collider?" T. Ludlam and L. McClerran, Phys. Today **56**(10), 54–61 (2003). (E)

An important signal for the dynamics of dense matter is the observation of hydrodynamic flow, in particular the sidewards flow of particles following an off-center collision. A rather large effect was found in the Au–Au collisions observed at RHIC. To interpret these measurements in terms of the equation of state of dense matter requires careful simulations (see Sec. VI C below), and there is not yet a consensus on the dynamical origin of the flow. The last prominent observable I will remark on is the correlation between particles in the final state, which is sensitive to the statistical properties of the phase where they were produced and interacted. For correlations between mesons such as pions, the correlation function is largely controlled by Bose statistics ("Hanbury–Brown–Twiss interferometry"). But correlations between other particles are also useful for extracting the statistical properties of the gas that produced them. A general review of the subject is

89. "Intensity interferometry in subatomic physics," D. H. Boal, C.-K. Gelbke, and B. K. Jennings, Rev. Mod. Phys. **62**, 553–602 (1990). (I)

The analysis of correlations at RHIC gave an overall source size of reasonable magnitude, but to date its shape is not yet well understood. See

90. "Correlations and fluctuations, a summary of quark matter 2002," S. Pratt, Nucl. Phys. A **715**, 389C–398C (2003). (A)

C. Simulations of ultrarelativistic collisions

Because the conditions of the collisions do not insure an equilibration, simulations of the reaction dynamics are essential for interpreting the experimental data in terms of the thermodynamic properties of hot dense matter. The initial stage of the collision is often treated by parton fragmentation, string breaking, or other phenomenological models of high-energy hadron interactions. At intermediate times, a hydrodynamic expansion is often assumed, or one may simulate the expansion by a Boltzmann cascade of a gas of interacting partons or quarks and gluons. At later stages, the hadrons are present and the Boltzmann dynamics can be applied to hadron interactions as was done in lower-energy physics (Ref. 76). Representative models of the different kinds are presented in the references below.

91. "Elliptic flow and freeze-out from the parton cascade MPC," D. Molnár and M. Gyulassy, Nucl. Phys. A **698**, 379–382 (2002). In this work the early phase of the collision is treated in a parton model; the partons scatter and are assumed to convert to hadrons during the course of the expansion. (A)

92. "Hydro plus cascade, flow, the equation of state, predictions and data," D. Teaney, J. Lauret, and E. V. Shuryak, Nucl. Phys. A **698**, 479–482 (2002). Here a hydrodynamic expansion is followed by Boltzmann dynamics in the hadronic final state. (A)

The predictions of many of these models were published before RHIC started operation and the answers were known. The outcome of that exercise is reported in

93. "On predictions of the first results from RHIC," K. J. Eskola, Nucl. Phys. A **698**, 78–87 (2002). (A)

VII. ACCELERATORS AND DETECTORS

I first list in Table I the accelerator facilities that have figured prominently in the advances noted in previous sections.

A. Experimental methods and detectors

Much of the progress in nuclear physics has only been possible owing to the development of very sophisticated accelerator facilities and detectors. A good example is the use of large arrays of germanium detectors for gamma spectroscopy of high-spin states. Some reviews of this and other purely experimental developments are

94. "Developments in large gamma-ray detector arrays," I. Y. Lee, M. A. Deleplanque, and K. Vetter, Rep. Prog. Phys. **66**, 1095–1144 (2003). (A)

95. "Low-Radioactivity Background Techniques," G. Heusser, Annu. Rev. Nucl. Part. Sci. **45**, 543–590 (1995). (I)

96. "Polarized gas targets," E. Steffens and W. Haeberli, Rep. Prog. Phys. **66**, 1887–1935 (2003). (A)

97. "Precision nuclear measurements with ion traps," G. Savard and G. Werth, Annu. Rev. Nucl. Part. Sci. **50**, 119–152 (2000).

98. "Low-temperature particle detectors," N. E. Booth, B. Cabrera, and E. Fiorini, Annu. Rev. Nucl. Part. Sci. **46**, 471–532 (1996). A calorimetric detector of the kind discussed here was recently used to measure the lifetime ($\tilde{1}0^{19}$ years) of a nucleus otherwise considered stable. (I)

99. "Experimental detection of alpha-particles from the radioactive decay of natural bismuth," P. de Marcillac *et al*., Nature **422**, 876–878 (2003). (I)

B. Applications of nuclear physics

An important application of radioactivity and accelerated ions is found in medicine for diagnostic purposes as well as therapy. The subject is covered in the textbook

100. Physics in Nuclear Medicine, 3rd ed., S. R. Cherry, J. Sorenson, and M. E. Phelps (Saunders, New York, 2003). (E)

Accelerators are needed for producing isotopes for positron annihilation imaging and for ion beams for therapy. See

101. "Molecular imaging with positron emission tomography," M. E. Phelps, Annu. Rev. Nucl. Part. Sci. **52**, 303–338 (2002). (I)

102. "The impact of nuclear science on life science," G. Kraft, http://www.nupecc.org/iai2001/report/B1.pdf. (E)

Nuclear techniques are indispensable for dating archeological artifacts and other objects.

103. "Archaeological dating using physical phenomena," Rep. Prog. Phys. **62**, 1333–1376 (1999). This review summarizes archaeological dating methods, mostly based on radioactive decay. (E)

104. "Particle accelerators for radiocarbon dating in archeology," M. Suter, Europhys. News **31**(6), 16–17 (2000). (E)

105. Radiation in Art and Archeometry, D. C. Creagh and D. A. Bradley (Elsevier Science, Amsterdam, 2000). (E)

There has been much discussion about using accelerators in combination with nuclear reactors to generate safer nuclear power and also to burn the long-lived transactinide wastes. See

106. Accelerator Driven Subcritical Reactors, H. Nifenecker, S. David, and O. Meplon (Institute of Physics, London, 2003). (I)

107. "Accelerator-driven systems for nuclear waste transmutation," C. D. Bowman, Annu. Rev. Nucl. Part. Sci. **48**, 505–556 (1998). (I)

Accelerators provide an important tool for low-energy neutron sources, used in biology and condensed-matter physics to determine structure by neutron diffraction. The issues associated with the production of neutrons and slowing them down are reviewed in

108. "Neutronics of pulsed spallation neutron sources," N. Watanabe, Rep. Prog. Phys. **66**, 339–381 (2003). (A)

Not all of the fundamental data needed for designing these machines is known, and this has given impetus to some of the reaction studies mentioned in Sec. IV.

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