Neutrons in science and technology

The neutral nucleon sees much use in research, ranging from particle physics to condensed-matter physics, and has applications in such diverse areas as mining, food preservation and art history.

D. Allan Bromley

In the four decades since the first controlled nuclear chain reaction made them available in abundance, neutrons have had a revolutionary impact on much of science and technology. Best known, perhaps, are the neutron's roles in energy production and nuclear medicine. However, this particle has made, and is making, enormous contributions in dozens of other areas of science and technology.

In this article we will look at a few of these other areas, emphasizing some of the neutron's more unusual applications. We will see, for example, how solid-state physicists are doping silicon by transmutation, how geologists are making chemical-element maps of the entire country, and how archeologists are using neutron-activation analysis to trace the origins of artifacts.

Much of the discussion will relate to the direct use of the neutrons themselves. No less important, however, are the radioisotopes produced through the exposure of elements to neutron fluxes in reactors. Thus far, nuclear scientists have studied about 1300 radioisotopes and 300 stable ones. But a vastly larger number are stable against immediate decay, and we know, for example, that when a uranium target is bombarded by high-energy uranium ions, such as those produced by the Berkeley Bevalac, over 6000 nuclear species are produced. The question arises—Who needs them? At long last we are entering the age of tailored radioisotopes. If clinicians or technologists now tell us that they want a particular chemical or biochemical behavior, a particular kind and energy of radiation, and a particular range of life-times, we have high probability of being able to provide all of them. As yet, we have only glimpsed the consequences of this new capability. Already, though, the isotope division of Oak Ridge National Laboratory alone reports annual sales of about four million dollars in stable isotopes and an equal amount in radioisotopes. Later, we will look at the use of gamma radiation from one of those radioisotopes—cobalt-60—in the preservation of food through bulk sterilization.

The earliest neutron sources were those comprising an alpha emitter in intimate contact with beryllium. Modern versions of these sources using plutonium-238, which has an 89-year halflife, or americium-241, which has a 458-year halflife, yield typical neutron fluxes of 5×10^{10} neutrons/second or about 5×10^{17} neutrons/year. Van de Graaff generators used in neutron production typically yield fewer than 10^{16} neutrons/year, and so give no major improvement in available fluxes. Electron linear accelerators yield about 10^{21} neutrons/year, and, like the Van de Graaff generators, give a measure of control over the neutron spectrum. Fission reactors, however, marked a major step forward, with a high-flux unit typically providing experimental fluxes of 10^{15} neutrons/cm^2 sec, or 10^{22} neutrons/cm^2 year. It is this enormous increase in flux that has made the neutron such an effective probe throughout science and technology.

It bears noting, too, that in terms of maximum attainable neutron fluxes, current nuclear-weapon designs yield up to 10^{29} neutrons/kiloton, and do so in about one microsecond. An elaborate technology has been developed to utilize this giant pulse of neutrons to determine neutron interaction cross sections via time-of-flight techniques.

Condensed-matter physics

It is in the case of condensed-matter physics that the neutron probe is uniquely powerful. There are several reasons for this. Because neutrons do not ionize the matter with which they interact, they accurately sample the bulk properties of that matter; through inelastic scattering or reactions induced at high energies, neutrons can introduce lattice distortions or impurities uniformly throughout the irradiated volume. Because of their intrinsic magnetic dipole moments, neutrons can probe bulk magnetization and spin phenomena. Finally, and most importantly, because thermal neutrons have momenta and energies that are well matched to the characteristic vibrational phonon energies of material lattices, they have unmatched power in probing the characteristics of these acoustic modes and thus the underlying interatomic forces of the solid.

In essence, in scattering studies the incident neutron beam illuminates the sample and is reflected by atomic planes. Obviously, vibrations of the atoms in these planes shift and distort the reflections. These vibrations are the so-called phonon modes. In general, however, there are other modes. In magnetic materials, for example, the individual atoms have intrinsic magnetic moments whose orientations are directly coupled to the intrinsic spins of these atoms. Because the neutron has a magnetic moment, it interacts with these atomic moments, and again from the characteristics of the reflections it is possible to deduce the magnetic structure of the lattice.

Physicists appreciated these features of thermal neutrons very soon after the construction of the first reactors. The first neutron spectrometer was mounted at a port on the Oak Ridge graphite reactor in the mid 1940s. Most of the research using neutrons to probe crystal lattices has used the so-called triple-axis spectrometer pioneered by Bertram N. Brockhouse at Chalk River.

D. Allan Bromley is Henry Ford II Professor of Physics at Yale University, in New Haven, Connecticut.

Neutrons from the reactor core are filtered and collimated and then monochromatized by Bragg scattering from a crystal on the first axis. These monochromatic neutrons are then scattered from the specimen on the second axis and analyzed on the third axis by yet another crystal scatterer before being detected. In this way, both energy loss to and energy gain from the specimen are readily measured, as are dispersion and, through choice of appropriate crystals or magnetic mirrors, polarization phenomena.

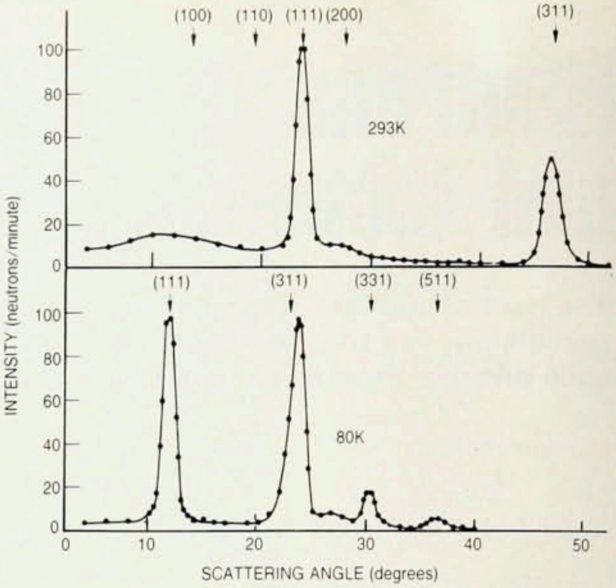
The box on page 35 contains a comprehensive listing of the many areas of condensed-matter physics to which neutron-scattering studies have already made very important contributions. Obviously, in a single article I cannot hope to provide complete coverage of so rich a scientific spectrum. What I have chosen instead is a very personal selection of studies to illustrate the range of physics accessible to the neutron probes.

Phonon and magnon interactions. In 1955, Brockhouse and Alec T. Stewart were the first to observe direct interaction of thermal neutrons with lattice phonons. In their experiment, neutrons traveling through a single crystal of aluminum both lost *and* gained energy through scattering, thus providing new information on the interatomic forces in the crystal lattice and the normal modes of vibration. Typical phonon modes in crystals have frequencies in the range of 10^{11} to 10^{13} Hz and wavelengths of about one angstrom, comparable to normal lattice spacings.

If one of the atomic moments is disturbed, its coupling with its lattice neighbors initiates a characteristic disturbance—the so-called spin wave, in which the precession angle changes by 2π radians, that is, by one full wavelength, after a number of interatomic distances. The energy required to establish such a spin wave—also called a magnon mode—obviously comes from the incident neutron. An established spin wave can give up energy to an incident neutron beam. This interaction depends on the magnitude of the atomic magnetic moment and on the orientations of the neutron spin and the atomic magnetic moment with respect to the scattering vector and with respect to each other.

Consequently, one can obtain detailed information on both the magnitude and orientation of magnetic moments in any substance that displays magnetic properties. Each type of magnetic lattice has a characteristic neutron scattering pattern. For paramagnetic materials, where the atomic moments are uncoupled and randomly oriented, the magnetic scattering is diffuse. For ordered magnetic lattices, the magnetic scattering is found in Bragg reflections.

Neutron-diffraction results, from an experiment on manganese oxide. The pattern seen below the Néel temperature of 122 K shows additional reflections due to scattering form an antiferromagnetic lattice. (Figure from Oak Ridge National Laboratory.)



Antiferromagnetic lattices are those in which the magnetic moments of the atoms become ordered spontaneously below a critical temperature, called the Néel temperature, but the ordered arrangement produces no net moment within the magnetic unit cell. The existence of this type of magnetic state was suggested by the French physicist Louis Néel in the early 1930s on the basis of macroscopic magnetic properties, and it was confirmed at Oak Ridge in 1949 by neutron-diffraction experiments on manganese oxide powder. This investigation is one of the classics in the field, and the diffraction patterns obtained at that time are shown in the figure above. These are patterns taken above and below the Néel temperature of 122 K. The room-temperature pattern contains only nuclear reflections corresponding to the atomic positions. In the pattern at 80 K, the additional reflections occurring at different angles are characteristic of scattering from an antiferromagnetic lattice. Not only did this investigation confirm the existence of antiferromagnetism, but it also gave the first experimental confirmation of the theory of indirect magnetic interactions, called superexchange. The antiferromagnetic coupling takes place indirectly through oxygen anions that are located between neighboring manganese atoms with antiparallel moments.

Magnetic phase transitions are of particular interest in modern physics. They present a special case of the general problem of phase transitions on which we have seen major progress in recent years, as witnessed by the award of the 1982 Nobel Prize in Physics to Kenneth Wilson of Cornell. To oversimplify, the goal of theoretical work in this field is that of reproducing experimental observations in the regions of the transition temperatures T_c as functions of temperature T in the form $(T - T_c)^{\beta}$, where β is the so-called critical exponent. What has been found is that this exponent depends almost not at all on the nature of the physical system under consideration and almost entirely on two simple parameters—the order of the phase transition and the dimensionality of the problem. This simplicity represents a triumph of theoretical insight. The total scattering cross section for neutrons on iron, for example, shows in the region of the Curie temperature typical behavior for a second-order phase-transition—second order in that it is the first derivative of the cross section rather than the cross section itself that is discontinuous at the Curie temperature. Microscopically, as iron approaches the transition temperature T_c, fluctuations in the alignments of the atomic moments become strong, long-range and slowly varying with time, so that the neutron-scattering cross section increases.

Iron is a typical three-dimensional magnetic system. However, there is also great interest in special systems that display effects of lower dimensionality. The complex crystal tetramethyl ammonium manganese chloride, called TMMC, is an almost ideal example of a one-dimensional Heisenberg antiferromagnet, and has been studied extensively at MIT and elsewhere. There are also a great many systems in which effective two-dimensional systems appear as sheets of magnetically coupled ions. Neutron-based measurements on such systems have provided some of the most critical data underlying our new understanding of phase phenomena. (See, for example, PHYSICS TODAY, July, page 17.)

Probing superconductors. Neutron scattering has also turned out to be a very effective probe for phenomena occurring in superconductors. In general, metals in the superconducting state expel any external magnetic field that is less than some critical strength.

For the class of superconductors known as type II, however, there is a field regime in which magnetic flux penetrates the otherwise diamagnetic matrix in the form of quantized tubes that are known as fluxoids. The fluxoids arrange themselves, depending upon the nature of the host crystal and the direction of the applied field, in a two-dimensional periodic structure known as the fluxoid or flux-line lattice. The spacing in these lattices is typically 1000 Å, which makes them suitable for study by small-angle neutron scattering. The first such studies, carried out in Saclay in 1964, found triangular flux-line lattices in niobium. More recent neutron-scattering studies have focused on the compound V_3Si, one of a very important group of high-field superconductors.

Utilizing radiation damage

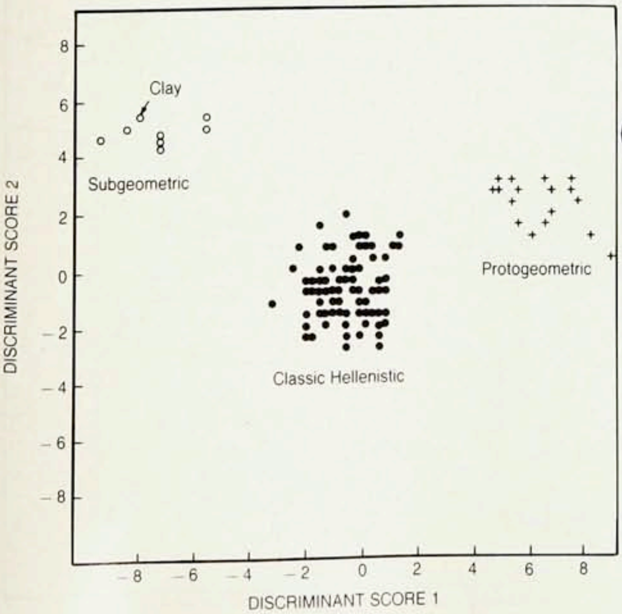
Neutrons do more than scatter when they interact with matter. It is well known, for example, that high-energy neutrons can transfer sufficient momentum to lattice nuclei to move them permanently from their normal lattice sites, creating dislocations and voids. Additionally, reactions such as (n,α) produce helium, which can collect to form bubbles that greatly reduce the mechanical integrity of the solid, result in flaking of its surface, or both. Obviously, such effects are of great importance in the construction of both fission and fusion reactors, for example, and much research has been devoted—with signal success—to the development of new alloys. These materials are designed to retain the desirable corrosion resistance, strength and other normal properties of stainless steel, while greatly reducing the development of voids and dislocations by making it easier for displaced lattice atoms to find their way back to normal lattice sites.

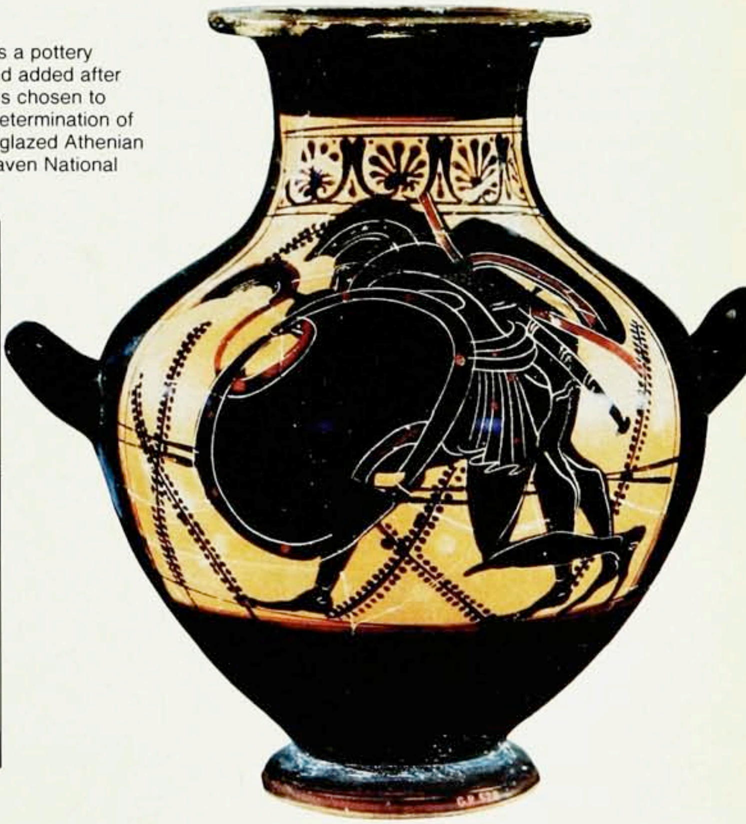
This cloud of radiation damage has a silver lining in the case of bulk neutron irradiation of silicon. Normal silicon has a 3.1% abundance of Si^{30}, which captures a neutron to form Si^{31}, which in turn decays with a halflife of 2.6 hours to form stable P^{31}. This phosphorus is *uniformly* distributed throughout the silicon to an extent totally beyond anything achievable by any other method of doping silicon with phosphorus as an electron donor impurity. Because of its uniformity of doping, this so-called neutron-transmutation-doped silicon is capable of handling high power levels when fabricated into devices such as rectifiers for use in bulk power transmission. It is also particularly well suited for the fabrication of infrared detectors, which require about 10^{12} phosphorus atoms/cm^3. Finally, because one can control the doping level with great precision by adjusting the applied neutron flux, neutron transmutation doping is increasingly being used to compensate for the inevitable traces of boron in all silicon, thereby producing what is effectively ultrapure intrinsic silicon from which the manufacture of devices can begin.

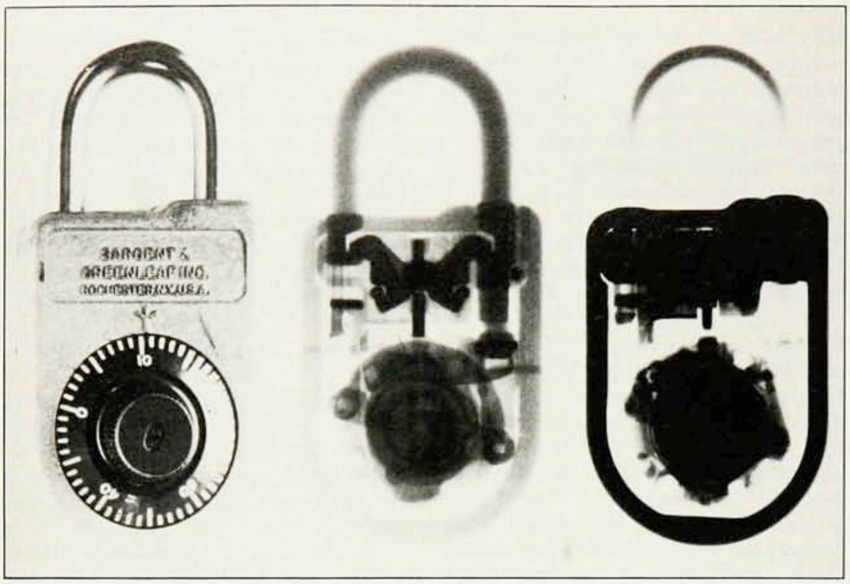
Current world production of neutron-transmutation-doped silicon is 50 metric tons per year. Annual production in the United States—at the University of Missouri and at CintiChems Inc.—is about 12 metric tons, and the demand is growing rapidly.

Finally, let me combine the last two applications and consider a very positive use of radiation damage in silicon. For a long time it has been recognized that as the density of integration of electronic devices on a single chip increases, the probability becomes appreciable that there will be errors caused, for example, by charges gener-

Compositional groups and vase. Each point in the plot represents a pottery fragment whose elemental concentrations have been calculated and added after being weighted according to two different schemes. The weighting is chosen to maximize the difference between compositional groups and allow determination of the site of production. The photograph shows an example of black-glazed Athenian pottery form the Classic period (480–320 BC). (Figure from Brookhaven National Laboratory.)







Combination lock as seen in a photograph (left), neutron radiograph (center) and x radiograph (right). To make a neutron radiograph, one places a "converter," usually a hydrogenous foil, over the photographic film, which registers protons knocked out by an incident neutron beam. Neutron imaging highlights the light elements, which preferentially scatter neutrons out of the beam. (Images courtesy of United States Department of Energy.)

ated along the ionization column of an alpha particle entering the device from contaminant uranium or thorium. These are the so-called "soft failures" of computer systems. Peter J. McNulty discusses this process in detail in his guest comment, PHYSICS TODAY, January, page 9.

At current levels of integration, the problem is particularly severe in charge-coupled devices because individual bits may be represented by no more than 50 000 electrons. According to James Ziegler of IBM and William Lanford of the State University of New York, the ultimate limitation is set by cosmic-ray neutrons creating recoil silicon ions and charged reaction products in the silicon. This source of soft failures becomes ever more important as the degree of integration is increased. Lacking any cure, the only remedy is vastly more complex—and expensive—error-correcting software. Happily, however, the same neutron that brings the problem also brings part of a solution!

Investigators using the University of Missouri reactor have found that fast-neutron irradiation of memory units in bulk can reduce their soft-error rate by a factor of 10. Apparently the radiation damage produced in the silicon substrate reduces the intrinsic resistivity sufficiently so that liberated charge along the ionization column of any incident charged particle dissipates much more readily and thus has a smaller probability of resetting a bit. Indeed, this bulk-neutron treatment frequently brings to life memory units previously discarded as nonfunctional!

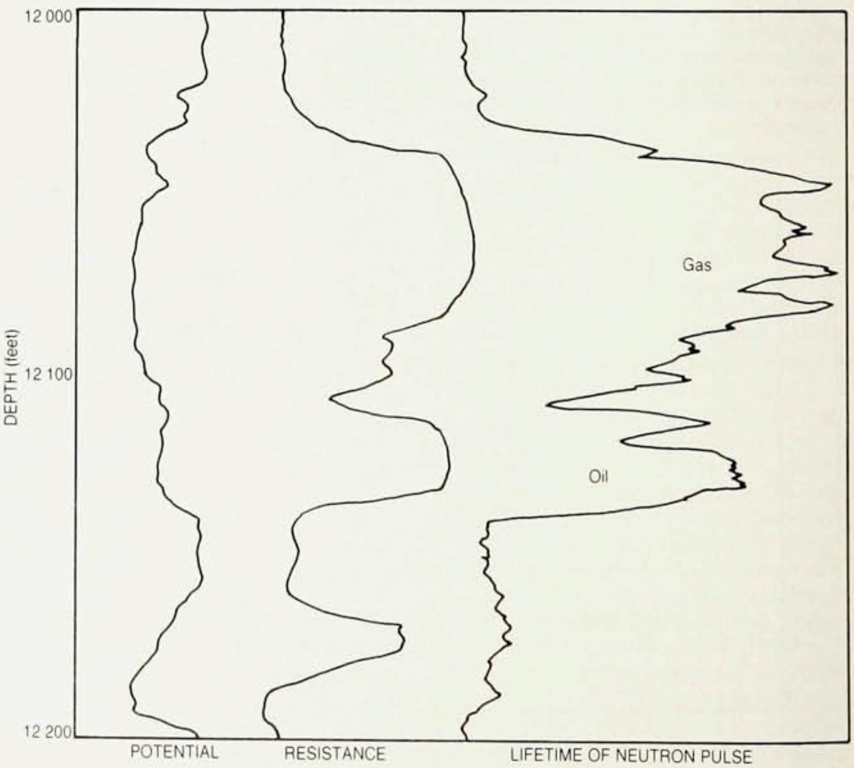
Neutron activation analysis

I turn now to the use of the neutron as an analytic probe of exquisite sensitivity. Perhaps the most familiar technique is that of neutron-activation analysis, where the sample is placed in a neutron flux; neutron capture then produces radioisotopes whose decay radiation is a unique signature for the elements originally present in the sample. There are two primary variants of this technique. In one, the irradiation and the radiation detection are separated in time by any convenient period, while in the other, the gamma radiation from the decaying radioisotopes is observed during the neutron irradiation. The latter technique is known as prompt-gamma neutron-activation analysis.

The sensitivity attainable differs from element to element, depending upon the capture cross sections and the technique used. Typical sensitivities of neutron-activation analysis, expressed as a fraction by weight of the sample, are 10^{-5} to 10^{-4} for sulfur and iron, 10^{-9} to 10^{-8} for zinc and mercury, and 10^{-12} to 10^{-11} for manganese and indium. These sensitivities are based on measurements following a one-hour exposure to a flux of 10^{13} n/cm^2 sec.

In prompt-gamma neutron-activation analysis, the sensitivity depends critically not only on the neutron capture cross section but also on the probability that the nucleus of interest emits a single strong gamma ray readily distinguishable from those characteristic of the surrounding material.

Archeology as well as paleontology draw on neutron-activation analysis. The first quantitative use of this technique to characterize archaeological materials was carried out in the chemistry department of Brookhaven National Laboratory in the mid 1950s.



Neutron scattering studies in condensed matter

Crystallography
- Crystal structures in materials containing hydrogen
- Crystal structures containing atoms close in atomic number
- Hydrogen bonding
- Hydrogen positions in a protein—myoglobin
- Ferrites
- Ferroelectrics

Magnetism
- Antiferromagnetic structures
- Ferromagnetic structures
- Superexchange mechanisms in magnetic compounds
- Magnetic properties of iron-group metals
- Magnetic properties of rare-earth metals
- Magnetic form factors
- Amorphous magnetism—spin glasses
- Production of polarized neutrons by diffraction
- Magnetic excitations
- Spin dynamics of iron and nickel

Lattice dynamics
- Phonon dispersion curves
- Interatomic forces
- Localized vibrational modes of impurities

Alloys
- Order-disorder in transition-metal alloys
- Magnetic-moment distribution in magnetic alloys

Liquids
- Structures of liquids
- Dynamics of liquids
- Rotons in helium-4
- Bose–Einstein condensate in superfluid helium-4

Superconductivity
- Flux-line lattices in Type II superconductors
- Magnetization distribution within a fluxoid
- Reentrant superconductors
- Coexistence of magnetism and superconductivity
- Electron-phonon interaction
- Phonon anomalies

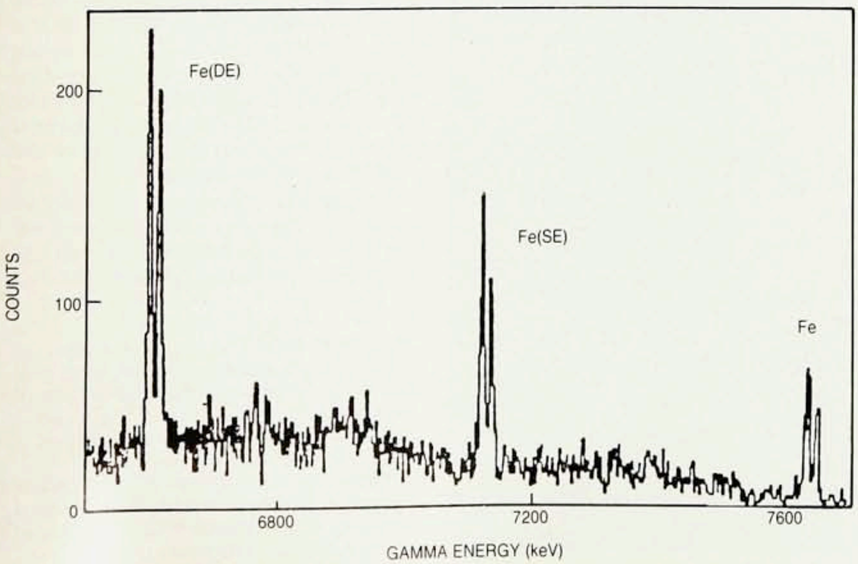
Phase transitions
- Soft modes and structural phase transitions
- Critical magnetic scattering and magnetic phase transitions
- Low-dimensional systems

Other
- Polymer conformations by small-angle neutron scattering
- Voids in irradiated materials by small-angle neutron scattering
- Voids in oil shale by small-angle neutron scattering
- Complex defects
- Electric dipole moment of the neutron
- Neutron interferometry

Based on material from Oak Ridge National Laboratory

Since then, many laboratories throughout the world have applied the technique to a great variety of materials, such as pottery, stone and minerals, glass, metals, paper and fabrics. In these studies, investigators usually measure a large number of trace components in many specimens, and then compare and group the results by multivariate statistical procedures. Specimens showing close agreement in the concentrations of many components are taken as having common origins, as the probability of obtaining such coincidence accidentally is very low.

Drillhole logs. Curves at the left show electrical potential, electrical resistance and the lifetime of a scattered neutron pulse, all as a function of the depth of a probe. Gas- and oil-bearing geologic strata reveal themselves most clearly to the neutrons. The gamma spectrum below indicates iron-bearing rock. Iron emits a characteristic gamma ray when it captures a neutron. (Figure from L. Rybach and A. H. Youmans; see bibligraphy.)



The usefulness of such trace-element characterization is illustrated by the recent analysis at Brookhaven of a large group of pottery fragments excavated in the ancient Agora of Athens. These specimens contained early pottery of the Protogeometric period (1000–900 BC) and Subgeometric period (750–650 BC) as well as the Classic (480–320 BC) and Hellenistic (320–30 BC) periods. In addition, specimens from Corinth and Aegina were analyzed for comparison. The figure on page 33 shows a plot of two discriminate functions, which are linear combinations of elemental concentrations chosen to maximize the difference between compositional groups. This demonstrates that the Athenian pottery of the Classic and Hellenistic periods have a consistent compositional pattern that differs significantly from that of earlier pottery from Athens and from the pottery of other Greek regions tested. Among the matching Classic and Hellenistic specimens are a number of pottery factory workshop "wasters" excavated from such workshops in the Agora itself. Therefore, one can be certain that pottery of this composition was indeed produced in Athens. The photograph shows a fine example of such Classic black-glazed Athenian pottery.

Art history. The world of art was not long in realizing that neutron-activation analysis opens an entirely new window through which the art treasures of the past might be viewed. The technique was developed at Brookhaven and is now used at a number of centers in this country and abroad. It involves exposing oil paintings to a broadly spread, highly purified thermal neutron flux of approximately 10^9 neutrons/cm^2 sec for periods up to one hour, generating within these paintings temporary, mild radioactivities. At various times after activation, one places x-ray film on the painting to record images that show the distributions of the most predominant radioactivities. A typical measurement of a painting involves a sequence of nine autoradiographic images. These images usually show significant differences from one another, as they are generally the records of radioactivities of quite different halflives. All of them are very different from the conventional x-ray image of the painting, which is largely determined by the distribution of the dense pigment lead white, a material that neutrons do not activate strongly. The activity that is primarily responsible for the autoradiograph is beta emission from the activated painting.

An interesting example of what autoradiography can reveal is provided by a study of the painting "Saint Rosalie Interceding for the Plague-stricken of Palermo," by Anthony Van Dyck, which is in the collection of New York's Metropolitan Museum of Art. A photograph of this painting is shown at the left in the figure on page 30 and its x-ray image is at the upper right. The x-ray image reveals details of a hidden underpainting—the face of a man, upside down near the bottom of the picture. It is difficult to interpret this overpainted face in the x-ray image, as it is masked by many details of the surface painting.

A neutron-activation autoradiograph of this painting, middle-right in the figure, taken only a few hours after activation, largely records the distribution of manganese, which is probably present as a component of the dark earth pigment umber. This radiograph shows details of the canvas where it had been filled in by an umber-tinted ground-paint layer. Two regions of loss are very noticeable in the upper center, where original areas of the painting have been replaced by modern repairs, which are free of manganese. The details of the figures in the Saint Rosalie painting can be seen to have the quality of drawings, and indeed art historians who have examined this autoradiograph believe them to be the underdrawings, in umber, of the original figures of the painting. It is interesting to note that the angel above and behind Saint Rosalie's head does not appear in the original underdrawing. Evidently this angel was added later in the development of the painting, a change in its initially conceived composition.

A later autoradiograph, shown at the lower right in the figure, was started four days after activation, and shows the overpainted man's head in remarkable detail. This autoradiograph is largely from the element phosphorus in the bone black used to define the head. Comparison of this autoradiograph with a self-portrait of Van Dyck, also in the Metropolitan's collection, shows that the overpainted picture is a portrait of Van Dyck himself.

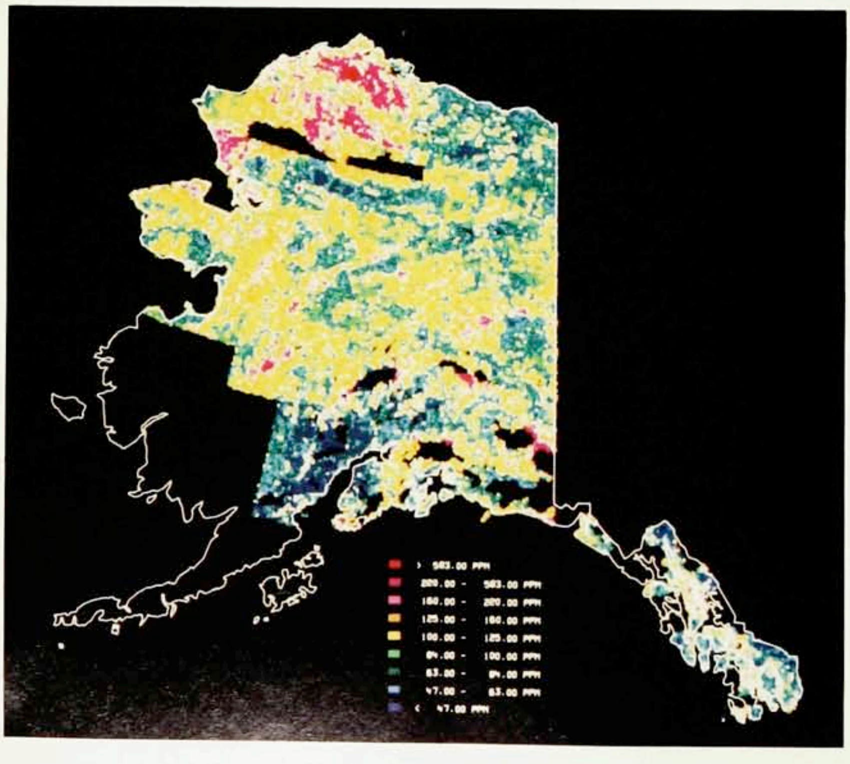
Obviously, this ability to unravel a painting gives art historians an entirely new dimension of analysis. One use they have made of autoradiography is to establish art fraud. (See Stuart Fleming's article on detecting art forgeries, PHYSICS TODAY, April 1980, page 34.) The well-known American artist Ralph Blakelock (1847–1919) was a prolific painter, but there has been a growing suspicion in art circles that some of the supposed Blakelocks are forgeries. An autoradiograph of a section of one of these paintings shows what appears to be the partially erased signature of Blakelock's daughter Marion, also a painter, strongly suggesting that someone attempted to pass off the work of the daughter as that of the father—with an eye to substantial profit.

Mining

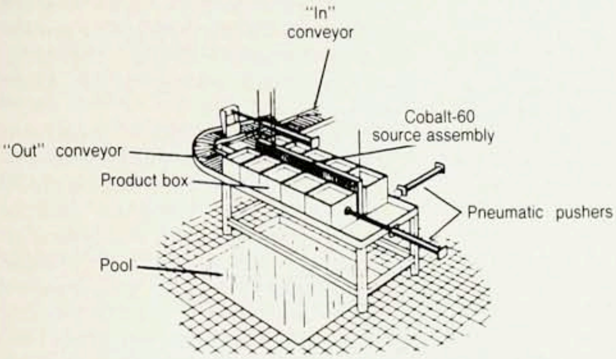
Neutrons have become of vital importance to the mining industry since geologists began using them to log geologic strata deep underground. The figure on page 35 illustrates two quite different aspects of this use.

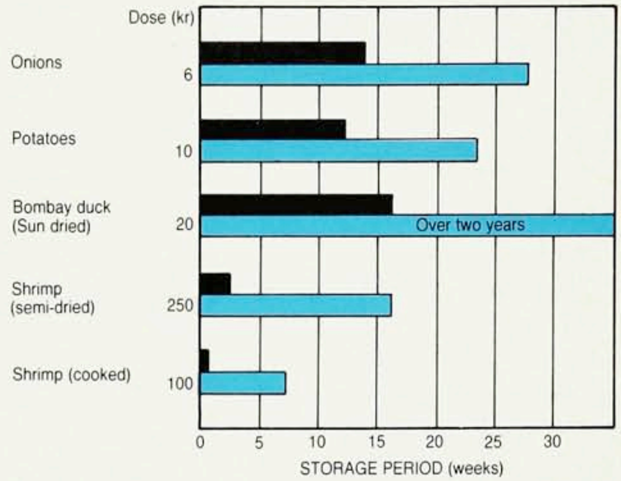
The typical exploration drill hole is some four inches in diameter; early use of neutrons in drill-hole logging used small sources based on the (α,n) reactions that take place when natural alpha-particle emitters are intimately mixed with beryllium powder. A typical drill-hole probe includes the neutron source followed by a heavy shield and a neutron counter. The counter is unable to see the source because of the shield, but is able to see neutrons scattering back from the surrounding rock. This counter is followed typically by a second shield and a gamma-radiation detector also able to view the rock but not the source.

The panel on the right in the figure shows the response of such a gamma-ray detector when the probe is in the vicinity of iron-bearing rock. We see

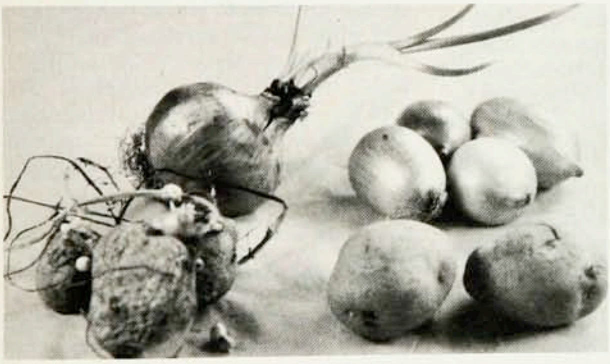


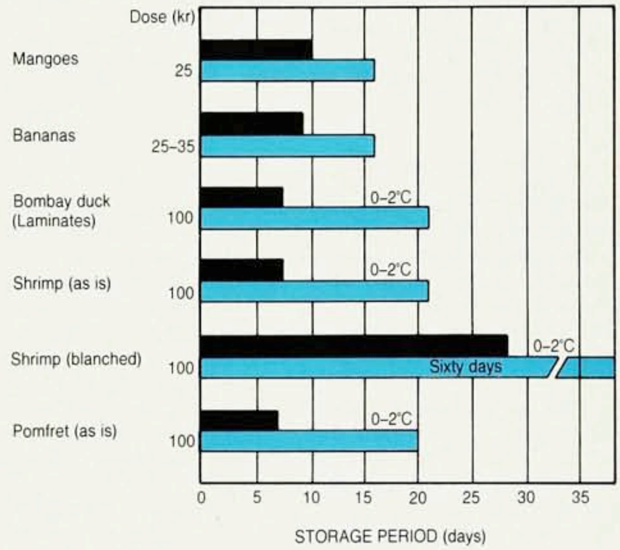
Chromium map of Alaska, showing the sedimentary distribution of the element over almost the entire state. Areas with chromium concentrations greater than 220 parts per million are shown in red. Yellow indicates 100–160 ppm, and blue indicates concentrations of less than 84 ppm. Data are from neutron activation analysis of samples collected on the ground. (Image from Los Alamos National Laboratory.)





Food irradiation for preservation. The continuous irradiator diagrammed here sits above a pool of water, which insulates the cobalt-60 gamma-ray source when it is not in use. Black and colored bars in the graphs show shelf lives of normal and irradiated foods respectively. Storage is at 25° to 30° C except where otherwise indicated. Photo compares unirradiated (left) and irradiated (right) potatoes and onions after equal periods of storage. Potatoes received 5 to 15 kilorads; onions, 10 kilorads. (Diagram and graphs from Bhabha Atomic Research Center, India. Photograph courtesy of Eugen Wierbicki, USDA Eastern Regional Research Center, Philadelphia.)



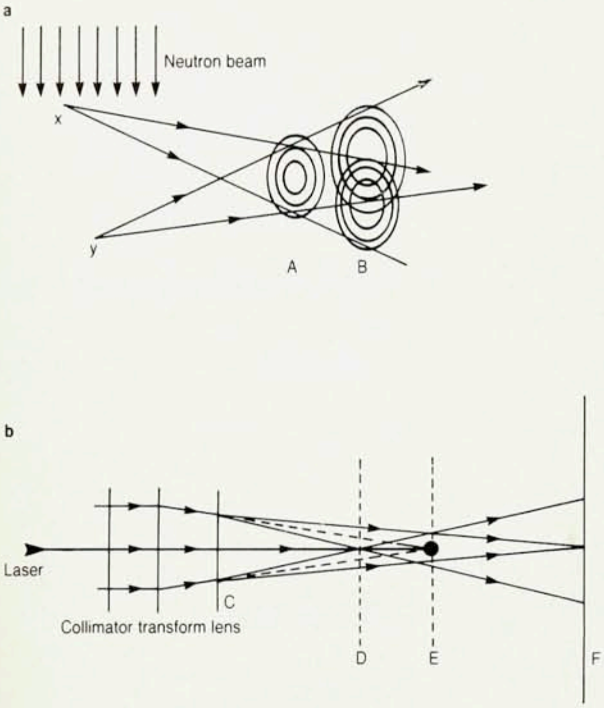


iron's characteristic neutron-capture gamma rays at full energy and in the single and double escape modes, where one or two annihilation photons escape undetected from the germanium gamma spectrometer. Inasmuch as each element has a characteristic gamma ray from radiative neutron capture, this technique has very wide applicability. The spectrum shown is very unusual in having essentially no confusing background; normally the geologist is faced with disentangling the signal of interest from a much more complex spectrum.

To detect hydrogen in the surrounding material—a characteristic signature of water, oil and natural gas—one monitors the neutron detector for enhanced neutron–proton scattering. By far more sensitive, however, are techniques in which the neutron source is pulsed and the neutrons are initially of higher energy—specifically 14 MeV. To this end, several companies have developed small self-contained Van de Graaff generators capable of descending the standard drill hole and generating 14-MeV neutrons via the (d,t) reaction. What is measured then is the effective lifetime of the neutron pulse following its emission from the accelerator target. One panel of the figure shows the result of such a measurement as a probe was lowered down a hole that penetrated both gas- and oil-bearing strata. Also shown here are the potential relative to a surface reference electrode and the resistance between two contacts carried by the probe. Notice that both the resistance and the neutron pulse lifetime increase dramatically in the gas- and oil-bearing regions. The resistance also rises sharply at greater depth but the neutron lifetime does not, showing that this stratum does not contain oil or gas. Typically, the neutron source operates at a pulse rate of 1000 Hz. The neutrons are emitted between 0 and 30 microsec. Gated neutron and gamma detectors sample the yield from 400 to 600 microsec, and again from 700 to 900 microsec before the cycle repeats. The neutron well-logging business amounts to many tens of millions of dollars each year in the United States alone.

The petroleum industry is discovering entirely new uses for neutrons as it considers the potential of the nation's oil shale to meet our energy needs. To assess the accessibility of such reserves, it is important to know the size distribution and anisotropy of the petroleum-bearing voids in these shales. Workers at Oak Ridge recently applied small-angle x-ray and neutron scattering to this problem.

Small-angle scattering measures structures of matter on a global scale, in the range of about 10 to 1000 angstroms. The scattering is produced by nonuniformities in density—the electron density in the case of x rays, and the scattering-length density in the



Neutron holography. The Fresnel zone plate at *A* focuses neutrons from the objects *x* and *y* on film at *B*. After demagnification, the hologram *C* produces real images with laser light. (From T. D. Benyon and A. G. Pink, University of Birmingham, England.)

case of neutrons. Small-angle scattering from shales occurs when the radiation passes from the solid matrix material to the voids. However, because the scattering length of hydrogen for neutrons is negative, the total coherent scattering length of CH_2 or H_2O is nearly zero, and filled pores scatter in a similar manner as the empty ones. This means that neutron scattering senses all the voids. On the other hand, to a first approximation the electron density of the petroleum in the voids is the same as that of the matrix, and the x rays sense mostly the empty voids.

In each case, analysis of the scattering data leads to a radial distribution of pore sizes. By detailed comparison of the x-ray and neutron-scattering data, it is possible to obtain the size distribution of the petroleum-filled voids and thus a measure of the economic potential of the shale in question.

In 1973 the Atomic Energy Commission initiated a vastly more ambitious program directed toward the mining industry. The National Uranium Resource Evaluation program was charged with making an airborne radiometric survey of the entire United States, with doing research studies on geologic mechanisms and environments that favor the concentration of uranium, and with carrying out a nation-wide hydrogeochemical survey of surface and ground waters and water-deposited sediments. In 1975 the mandate was expanded and became the Hydrogeochemical and Stream Sediment Reconnaisance survey, and the scope was broadened from uranium to cover other strategic elements as well. Los Alamos has specific responsibility for a number of western states and for Alaska. The map on page 36, based on neutron-activation analysis of samples collected on the ground, shows typical data for Alaska, giving the sedimentary distribution of chromium in parts per million over almost the entire state. Surveyers use short-delay neutron-activation analysis on samples to collect data for Al, Ba, Ca, Cl, Dy, K, Mg, Mn, Na, Sr, Ti and Va. Long-delay neutron-activation analysis gives data on Au, Cl, Co, Cr, Cs, Eu, Fe, Ha, La, Lu, Ru, Sb, Sc, Sa, Ta, Tb, Th, Yb and Zn. This program thus gives a detailed overview of the mineral resources of the country and is an invaluable aid to coherent planning. Only neutron-activation analysis provides the speed, specificity, broad spectrum and low cost that makes so extensive a program feasible.

Intense gamma sources

Everyone is familiar with the use of fission products such as Co^{60} and Cs^{137} as sources of intense gamma radiation for clinical medicine. However, these gamma sources have other important uses. One that has not been taken advantage of to any extent in this country for other than medical purposes is bulk sterilization. In India, however, where the need is more pressing and obvious, bulk sterilization of food is being introduced on a broad scale.

Because India lacks adequate storage and refrigeration facilities, over 30% of all foodstuffs there are wasted through spoilage. Moreover, lacking adequate refrigerated transport, India has not been able to translate its major protein source—the ocean—into one that benefits more than coastal areas, again because of spoilage.

The figure on page 37, with data from USDA and the Bhabha Atomic Research Center in Trombay, India, shows a bulk irradiator based on gamma radiation from cobalt-60; it is typical of those now in use for fruits, vegetables and packaged foods. The graph shows some of the current results for the extensions in shelf and transport lifetimes of various foods. The gain from irradiation is clearly enormous, but it is best measured in terms of the millions of humans saved from starvation in India alone. This technique is widely applicable in the developing world, where spoilage is a particular problem and where the energy-intensive methods of storage and preservation characteristic of the developed world are frequently out of the question. Widespread use of radiation sterilization of foodstuffs could have a greater impact on the problem of world hunger than any other single development.

This field has lagged in the developed world through lack of perceived need and through widespread psychological aversion to eating anything "contaminated" with radiation. It merits reexamination.

Particles and waves

To end this article I would like to mention some interesting facts about ultracold neutrons and discuss briefly a new technique that makes neutron holography possible.

Whereas thermal neutrons have a mean energy of about 0.025 eV and a mean velocity of about 2200 m/sec, ultracold neutrons, by definition, have energies of about 10^{-7} eV and velocities of about 5 m/sec. One can store ultracold neutrons in containers made of ordinary materials such as metal or glass, which at such low energies are totally reflecting, or by taking advantage of the interaction between suitably chosen magnetic fields and the neutron's intrinsic magnetic moment. These two techniques have attained storage times of up to about 330 seconds and over 1000 seconds, respectively.

Dispensing these neutrons is interesting. A one-meter increase in height in the Earth's gravitational field corresponds to a change in neutron energy of 10^{-7} eV, so that a rotating crank section in a neutron guide having a radius in excess of one meter can open or close the guide completely. Magnetic control is also possible.

The wave properties of neutrons

have technological implications: Neutron holography is a very new and potentially very important development in the use of neutrons, holding the potential for three-dimensional delineation of features *inside* completely closed solids. The figure on the opposite page illustrates the technique. At the top, a neutron beam illuminates two point objects x and y in space. A Fresnel zone plate composed of alternate rings of gadolinium and aluminum sits at point A. Behind it, in the plane at B, is x-ray film. To view the hologram produced at B, one demagnifies it optically and illuminates it with a converging laser beam. As shown at the bottom of the figure, the demagnified hologram at C produces a real image of the objects in plane F. However, because the objects x and y were different distances from the Fresnel zone plate, their real images appear at different distances from the hologram. This neutron holographic technique is still in its infancy, but it holds high promise of interesting and perhaps unique technological applications.

We have seen in this article just a few snapshots of the enormous scientific and technological terrain to which the neutron has made, and continues to make important contributions. I can say that in these areas, uniformly, the impact has been both benificent and benevolent.

* * *

This article is based on a more extensive paper given at the University of Chicago 1 December 1982, at a symposium commemorating the fortieth anniversary of the first artificially produced, self-sustaining nuclear chain reaction. The paper will appear in full in the proceedings of the symposium, which are being edited by Robert G. Sachs of the University of Chicago.

I would like to take this opportunity to express my deep appreciation to the following persons who responded so generously to my requests for information and other input to this article: Gil Bartholomew, Henry Hurwitz, James Leiss, Walter Massey, A. M. L. Messiah, Norman Ramsey, Louis Rosen, Nicholas Samios, David Shirley, Tom Tombrello and Alex Zucker.

Thanks also go to Bob Sachs and to Hanna Gray for their invitation to participate in the fortieth-anniversary symposium and for the stimulus required to make me pull together the material contained herein.

As always, I am indebted to Mary Anne Schulz, Rita Bonito and Sandy Sicignano for their assistance in the preparation of this article.

Bibliography

The following list of papers and books is presented to aid readers who seek further information on the applications of neutrons.

- P. W. Aamodt, *Hydrogeochemical and Stream Sediment Reconnaisance for Uranium and Other Strategic Elements*, Los Alamos Nat. Lab. Report 77–34 (December 1977).
- M. W. Ainworth, J. Brealy, *Art and Autoradiography: Insights into the Genesis of the Paintings of Rembrandt, Vandyke, and Vermeer*, Metropolitan Museum of Art, New York (1982).
- L. W. Alvarez, W. Alvarez, F. Asaro, H. V. Michel, "*Extraterrestrial Cause for the Cretaceous–Tertiary Extinction*," Science **208**, 1095 (1980).
- W. Alvarez, F. Asaro, H. V. Michel, L. W. Alvarez, "*Irridum Anomaly Approximately Synchronous with Terminal Eocene Extinctions*," Science **216**, 886 (1982).
- J. D. Axe, G. Shirane, "Exploring phase transformations with neutron scattering," PHYSICS TODAY, September 1973, page 32.
- G. E. Bacon, *Neutron Scattering in Chemistry*, Butterworths, London (1977).
- H. Berger, *Neutron Radiography*, Elsevier, New York (1965).
- T. D. Begnon, A. G. Pink, "Neutron Holography Using Fresnel Zone Plate Encoding," Nature **283**, 749 (1980).
- R. J. Birgeneau, G. Shirane, "Magnetism in One Dimension," PHYSICS TODAY, December 1978, page 32.
- R. Colella, A. W. Overhauser, "Neutrons, Gravity and Quantum Mechanics," American Scientist **68**, 70 (1980).
- G. Fidecaro, *The Grenoble Neutron Oscillation Experiment*, CERN report EP/81-136 (1981).
- R. L. Fleischer, P. B. Price, R. M. Walker, "Tracks of Charged Particles in Solids," Science **149**, 383 (1965).
- R. L. Fleischer, "Where Do Nuclear Tracks Head," American Scientist **67**, 194 (1979).
- R. Golub, J. M. Pendelbury, "Ultra Cold Neutrons," Rep. Prog. Phys. **42**, 440 (1979).
- R. Gregg, T. A. Tombrello, "Sputtering of Uranium," Radiation Effects **35**, 243 (1978).
- V. P. Quinn, "J. F. K. Assassination: Bullet Analysis," Analytic Chemistry **51A**, 484 (1979).
- E. T. Jurney, "Application of the Thermal (n,γ) Reaction to Elemental Analysis," in *Neutron Capture Gamma-Ray Spectroscopy*, R. E. Chrien, W. R. Kane, eds., Plenum, New York (1979).
- A. R. Mackintosh, *Neutron Scattering and Magnetism*, H. C. Oersted Institute Preprint, U. of Copenhagen (1982).
- I. Perlman, F. Asaro, H. V. Michel, "Nuclear Applications in Art and Archeology," Ann. Rev. Nucl. Sci. (1972), page 383.
- I. Peterson, "A Nuclear Change for Silicon," Science News **122**, 45 (1982).
- N. F. Ramsey, "Electric Dipole Moments of Elementary Particles," Rep. Prog. Phys. **45**, 96 (1982).
- L. Rybach, A. H. Youmans, "New Nuclear Logging Methods," Bull. Ver. Schweiz. Petrol.-Geol. u. Ing. **35**, 34 (1968).
- D. D. Warner, R. F. Casten, W. F. Davidson, *An IBA Description of the Collective States of* ^{168}Er, Brookhaven report BNL-29378 (1982).
- J. F. Ziegler, W. A. Lanford, "The Effect of Cosmic Rays on Computer Memories," Science **206**, 776 (1979). □