Q3D spectrometer at Los Alamos provides high-precision measurements of the energies of charged particles produced in nuclear reactions. The projectiles come from a tandem Van de Graaff through the tube at left and interact with the target in the chamber being worked on in the center. The spectrometer magnet swings along the track around the target to provide measurements at various angles. Figure 1

Nuclear spectroscopy

The study of how nuclei absorb and emit energy has progressed dramatically in the last few decades and has effects in fields as diverse as astrophysics and medical diagnostics.

Fay Ajzenberg-Selove and Ernest K. Warburton

Nuclear spectroscopy can be defined as the study of how nuclei absorb and emit energy. It is particularly concerned with the properties of individual levels such as energy, angular momentum (spin), isospin (the embodiment of the basic equivalence of neutrons and protons), magnetic and electric moments and transition rates and so forth. Our knowledge of these properties has increased rapidly and dramatically since 1945. This nearly exponential advance has occurred because of tremendous technical advances in equipment, in experimental methods, and in analyzing experimental data. Figure 1 shows one example of the sort of spectrometers available to nuclear physicists today. The use of the computer in analysis has been especially important in the last 15 years. In this article we will try to convey a feeling for the diversity and sophistication of present-day nuclear spectroscopy; we will concentrate on those areas where in recent years the most progress has been made in our understanding of the properties of nuclear levels.

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Nuclear models

Nuclear spectroscopy is not an end in itself. We study the parameters of nuclear states for many reasons. Perhaps the major aim of nuclear physics is to understand how nucleons behave within a nucleus. Nuclear spectroscopy sometimes contributes to this goal in a direct way, but more commonly spectroscopic data are used to extract the properties and wavefunctions of nuclear levels and thus contribute to theories for predicting them.

Even if we were to understand the nuclear force acting within nuclei as well as we understand the electromagnetic force, nuclear structure would still be a complex and formidable many-body problem. The nuclear spectroscopist's approach is to use various models of the nucleus to mediate between the experimental results and the fundamentals of nuclear theory. Thus, for example, one often considers "free" nucleons under the influence of an effective interaction that represents the forces due to the remaining nucleons; such models compensate for our inexact knowledge of nuclear forces and for the limitations on computational time and space. When one compares experimental results with a nuclear model, the first step is usually to look at the spectra of energy levels of known spin and parity. Thus, determining the energies, spins and parities of the quantum states of nuclei is probably the most important aspect of nuclear spectroscopy.

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The shell model rests on the fiction that a few valence nucleons move in a potential due to the bulk of the nucleons. This turns out to be a very good approximation for experimentally observable parameters that reflect the individual action of nucleons, but is poorer for those observables that show the effects of the collective behavior of the nucleons. In such cases, the so-called collective models are more appropriate. For instance, in areas of the periodic table where nuclear shapes have strong departures from simple spheres, the shape usually has a quadrupole character; states in the band generated by rotation of the nucleus are connected by electric quadrupole (E2) transitions, and the nuclear structure is remarkedly well described by a collective model, which, in its simplest form, is a simple rigid rotor. More sophisticated models combine features of the shell model and the collective model. In recent years, the "interacting-boson model" has been applied with surprising success in several areas of the periodic table. As in the case of electrons forming stable pairs that act as bosons in the case of superconductivity, nuclear forces favor the pairing of nucleons; these nuclear pairs, which are bosons, are simpler entities to treat than two individual nucleons. Calculations based on this model have predicted new symmetries in nuclei, which were subsequently discovered. In addition, identifying the bosons as pairs of valence fermions allows one to relate changes in collective structure directly to changes in the number of valence nucleons available. The predictive power of all these nuclear models has improved dramatically in recent years.

In the most successful versions of the shell model the effective interaction is determined by a least squares fit to the energies of levels whose spin and parity is known after the configurations of the levels have been determined by experiment. One usually starts by fitting those parameters of the wavefunction that are not sensitive to small admixtures from other states, such as electric quadrupole moments and transition rates and single-nucleon spectroscopic factors. Finally, the model results are tested by comparing them to more exacting properties, such as other electric and magnetic transitions and moments as well as β-decay matrix elements.

Specificity

In 1983, nuclear physicists have at their disposal beams of particles ranging from electrons, muons, pions, kaons and neutrons, to ions of many elements throughout the periodic table, including radioactive ions such as tritons, H^3, and C^{14}. A wide variety of machines produce these beams over an energy range varying from a small fraction of an electron volt to several GeV. This diversity of nuclear probes is crucial to our exploration of the nucleus.

In general, the probes induce nuclear reactions, and from the products of the reactions we try to determine the properties of the individual energy levels. Identifying and understanding the mechanisms by which the reactions proceed is thus a vital part of the work of a nuclear spectroscopist. Because we have a far from complete understanding of the strong interaction, our knowledge of reaction mechanisms is necessarily approximate. Fortunately, there is usually one dominant interaction between a probe and the nucleus, so that each variety of probe measures predominantly the matrix elements of one operator. The converse of this insight is the rule of specificity introduced by Aage Bohr and Ben Mottelson: For each nuclear property there is one type of probe best suited to study it.

For instance, electron beams interact with the nucleus through the electromagnetic interaction, which is well understood; electrons are thus well suited to measuring the properties of electromagnetic transitions. Another example is the measurement of the "spectroscopic factor" $S(x)$ of the nucleon (or nucleon cluster) x for a nuclear state in the nucleus with $A + x$ nucleons formed from the ground state of the nucleus with A nucleons; this spectroscopic factor is an indication of the similarity between the ground-state wavefunction and that of the cluster $A + x$. This factor is best measured[1] by a transfer reaction such as $Bi^{210m}(t,\alpha)Pb^{209}$ in which x nucleons (in this example, one proton) are transferred between the initial and final nucleus. The resolution available in such measurements is about 3 parts in 10 000 in energy, and thus gives very precisely determined energy levels in the final nucleus—Pb^{209} in this case. This particular example is also interesting in that the bismuth-210m target is itself radioactive, with a halflife of 3 million years, and has the highest spin of any target used to date (its J^{π} is 9^-). (See figure 2.)

The number and diversity of the available probes and the specificity of their interactions allow us to overcome to a great extent the inseparability of reaction mechanisms and the underlying structure, allowing us to determine many nuclear properites with great precision.

Types of reactions

Different types of nuclear reactions can be characterized by the distance of closest approach between target and projectile. Very roughly, Coulomb excitation takes place via the long-range electric interaction at distances on the order of 10 fm. Direct reactions such as the transfer of nucleons and elastic and inelastic scattering via the nuclear force take place through peripheral collisions while complete fusion followed by fission or other processes can occur when there is appreciable overlap of projectile and target. Nuclear reactions are conveniently denoted by a shorthand notation, A(x,y)B, in which the target nucleus is A and the projectile is x; the reaction produces B with the emission of y.

Transfer reactions. The charged particles emitted in a direct nuclear reaction are often analyzed according to their momentum in a magnetic spectrometer. For instance, the data of figure 2 were taken with the spectrometer shown in figure 1, which consists of one quadrupole and three dipole magnetic lenses. Several such "Q3D" spectrometers are in use throughout the world. They are particularly well suited to high-resolution heavy-ion detection (that is, for ions with mass numbers larger than about 3) and have played a crucial role in the study of heavy-ion inelastic scattering and transfer reactions. These reactions remained essentially uninvestigated until 1970 when Q3D spectrometers became available. Figure 3 illustrates[2] the sensitivity of heavy-ion transfer reactions, which can be used to select particular final states. In each of the two reactions shown, Sm^{148} picks up a neutron to form Sm^{149}; in graph **a**, the neutron comes from O^{16}, in **b** it comes from C^{12}. The importance of heavy-ion transfer is underlined by noting that the three indicated states were not observed in earlier studies in which Sm^{148} picked up a neutron from deuterium. Apparently, transfer of nucleons from light or heavy ions is highly selective in populating states of low or high angular momenta respectively.

The development of software for on-line computers has been of great importance to the use of magnetic spectrometers, such as the Q3D, for complex reactions. The software permits changing electronic parameters and immediately observing the changes that result from new setting of gates, etc. One can thus rapidly discriminate between the various kinds of particles going through the spectrometer. The computer displays can also be used to obtain a great deal of simultaneous information on different particles, each with its own gating. One can, for instance, gate time of flight vs. energy loss and the energy vs. the position of the particles, along the focal plane of the spectrometer. One recent application of such techniques involved bombarding Ne^{20} nuclei with α particles.

The dominant product is He^6 nuclei (and, of course, α particles). However, in rare cases (a few per million) the Ne^{20} nucleus transfers an entire α particle to the incident He^4 nucleus, forming the nuclei He^8 and Ne^{16}, the reaction denoted by $Ne^{20}(\alpha,He^8)Ne^{16}$. The alphas came from the 88-inch cyclotron at Lawrence Berkeley Lab, and the products were analyzed with a quadrupole–sextupole–dipole spectrometer.[3] By successively gating the counts, first to eliminate protons, deuterons and tritons, and then to restrict the time of flight, the differential energy loss and the energy to just those values appropriate to $He^8 + Ne^{16}$, the LBL group was able to pick out the 22 He^8 particles from more than 10 million others and thus determine the mass of the unbound Ne^{16} nucleus.

Elastic and inelastic scattering. In the last decade, high-resolution, high-energy beams of protons, neutrons, pions, electrons and so on have become much more widely available—and hence much more widely used as nuclear probes. All these probes constitute a powerful tool for the selection of different modes of excitation built on ground states. For instance, by comparing π^+ and π^- inelastic scattering one can untangle the contributions of neutrons and protons to a given transition rate. One can also use deuterons and alpha particles to select isoscalar transitions (that is, transitions that do not change the isospin) and electrons to select isovector (isospin changing) dipole transitions. By contrast, protons and neutrons are nonselective probes. No results have improved more dramatically than those from electron scattering. The new generation of high-resolution electron-scattering facilities such as those at the Bates linear acclerator lab in Massachusetts and the Saclay accelerator in France, together with dispersion-matched magnetic spectrometers, provide resolutions of a part in 10^4 for electrons with energies of 100–400 MeV, thus allowing the separation of most low-lying nuclear levels via inelastic scattering. By varying the angle or energy of the scattered electrons, one can vary the momentum $\mathbf{q}$ transferred in the reaction and thus map out the transition density ρ versus the nuclear radius $\mathbf{r}$. (The scattering intensity at $\mathbf{q}$ is related to the Fourier transform of $\rho(\mathbf{r})$.) The traditional electric and magnetic moments, or transitions, correspond to the point at $\mathbf{q} = 0$. Thus, electron (and, to a lesser extent, hadron) scattering provides a new dimension (the $\mathbf{q}$-direction) of observables for comparison to theory.

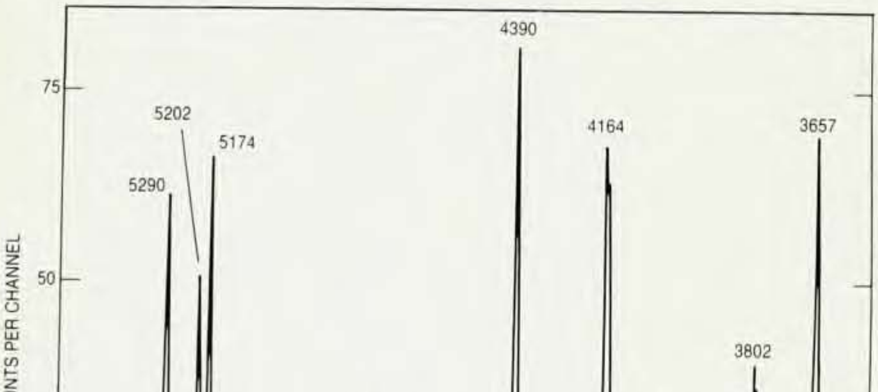
Multiple Coulomb excitation. Coulomb excitation, in which one nucleus excites another via their Coulomb interaction, is a very well understood electromagnetic phenomenon. In the 1950s, for example, knowledge about Coulomb excitations contributed to the discovery of highly deformed rotational nuclei and to the development of the rotational model. In recent years, Coulomb excitation has been used to probe to very high spin the E2 ground-state bands of deformed nuclei. For high-Z projectiles and targets, the probability p of Coulomb excitation at energies (and thus distances) just below those at which nuclear reactions take place approaches unity. A nucleus with an even number of protons and neutrons can be successively excited n times ($0^+ \rightarrow 2^+ \rightarrow 4^+$, and so forth), and one finds experimentally that the probability p^n is still significant even for n as large as 15, that is, for spins as large as 30. Multiple Coulomb excitation has thus become a powerful tool for the investigation of ground-state rotational bands.

Another technical advance that has contributed to these investigations is the development of large germanium gamma-ray detectors having resolutions around 2 keV for 1-MeV gamma rays. These detectors, in fact, revolutionized gamma-ray spectroscopy in the 1960s and 1970s.

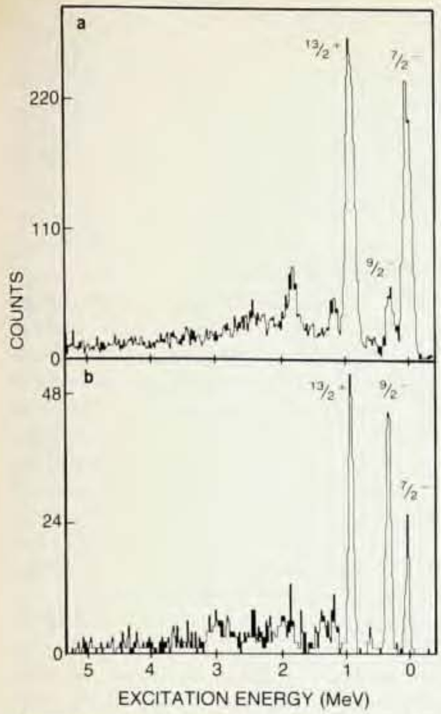
As a specific example of these techniques, consider an experiment performed by Eckart Grosse and his collaborators[4] at the Gesellschaft für Schwerionenforschung in Darmstadt, West Germany, in which a beam of Pb^{208} ions (with an energy of 5.3 MeV per nucleon) is used to excite U^{238} nuclei in a thin foil target. By counting the gamma rays in coincidence with the scattered projectile and recoiling target nuclei, the GSI group obtained a gamma-ray spectrum for ground-state rotational-band angular momenta up to $J = 30$. (The gamma rays are emitted as the rapidly spinning nucleus slows down to zero angular momentum.)

In the Coulomb excitation of one heavy nucleus by another, the center-of-mass velocities encountered are about 7% of the speed of light. Thus, the gamma rays emitted from a thin target are strongly Doppler shifted and have energies strongly dependent on the relative direction of the recoiling nucleus and the gamma-ray detector. Without a correction for the Doppler shift, the peaks near the top of the band would be smeared out and very difficult to observe. To perform the correction requires a computer for on-line analysis of data: A signal from the position-sensitive detection of the recoiling nucleus and projectile (simultaneous) is used to correct the gamma-ray signal for the Doppler shift before the gamma-ray spectrum is displayed.

The Doppler shifts, unwanted in this example, can be useful in other ways: for example, to measure nuclear life-



Spectrum of α-particles for the Bi^{210m} (t,α) Pb^{209} reaction. The numbers above the peaks are excitation energies in keV for Pb^{209}. The width at half maximum of a typical peak is 10 keV for α-particles having a kinetic energy of 30 MeV—this is an energy resolution of 3×10^{-4}. The target is unique in that it is radioactive, a metastable state at 271 keV with a halflife of 3×10^6 years, and has the highest spin, $J^\pi = 9^-$, of any target used to date. (Adapted from reference 1) Figure 2



Single-neutron transfer reactions. In both cases the target nucleus is Sm^{148}, which accepts a neutron to become Sm^{149}. In **a** the projectile is O^{16} at 120 MeV; in **b** the projectile is C^{12} at 90 MeV. Note the sharp difference in the relative population of the final states (labeled with their J^{π} values). (Adapted from reference 2.) Figure 3

times. For instance, if the thin uranium target used in this experiment is backed with a material thick enough to stop the recoiling U^{238} nuclei, they will emit gamma rays while slowing down. The slowing-down process, which is fairly well understood, takes on the order of 10^{-11} sec and provides a time scale against which to measure the lifetimes of the states. For lifetimes very long compared to 10^{-12} sec there is no Doppler shift, while for lifetimes much shorter than 1 psec there is a full Doppler shift. For intermediate lifetimes the intermediate Doppler shift can be analyzed to yield the lifetime. Sophisticated methods based on the Doppler effect and a wide variety of nuclear reactions have been developed for measuring nuclear lifetimes (and thus transition matrix elements) in the range 1 nsec to 1 fsec.

Radiative neutron capture. When a nucleus captures a neutron, the product nucleus is excited and decays to the ground state via a cascade of gamma rays. The statistical nature of the capture itself and of the radiative cascade ensure the population of a broad range of low-lying states, unrestricted by structure-dependent selection rules. The only practical restriction stems from angular-momentum selection rules, which limit the spin of the final states to within a few units of that of the capture state. Thus the (n,γ) reaction has little specificity—in marked contrast to most other nuclear reactions. As such it represents an ideal tool to test nuclear models that purport to offer a complete description of low-lying states. To fit data from radiative neutron capture experiments, it is necessary to determine not only whether the theory predicts certain properties of particular nuclear levels correctly, but also whether the complete set, and only the complete set, of observed levels is generated by the model.

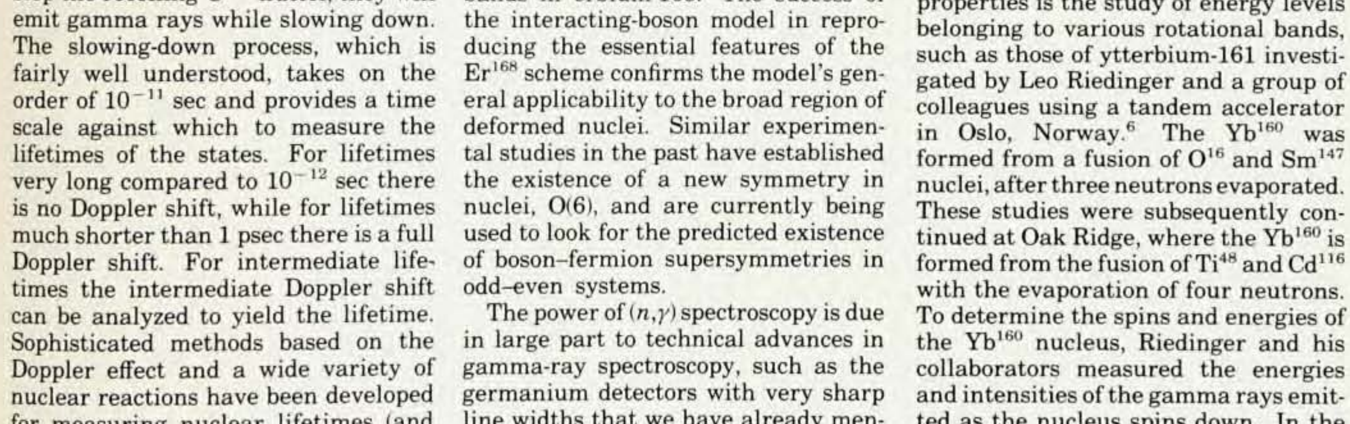
The interacting-boson model provides an excellent example of such a theory and, indeed, many of the important verifications of its broad applicability have stemmed from recent (n,γ) studies. One example[5] is shown in figure 4, where we compare the experimental and the predicted sequence of low-spin positive-parity rotational bands in erbium-168. The success of the interacting-boson model in reproducing the essential features of the Er^{168} scheme confirms the model's general applicability to the broad region of deformed nuclei. Similar experimental studies in the past have established the existence of a new symmetry in nuclei, O(6), and are currently being used to look for the predicted existence of boson–fermion supersymmetries in odd–even systems.

The power of (n,γ) spectroscopy is due in large part to technical advances in gamma-ray spectroscopy, such as the germanium detectors with very sharp line widths that we have already mentioned. These allow one to resolve most gamma transitions even in the heaviest nuclei to obtain accurate intensity measurements, and allow one to determine gamma-ray energies with accuracies of several parts in a million.

High spin states

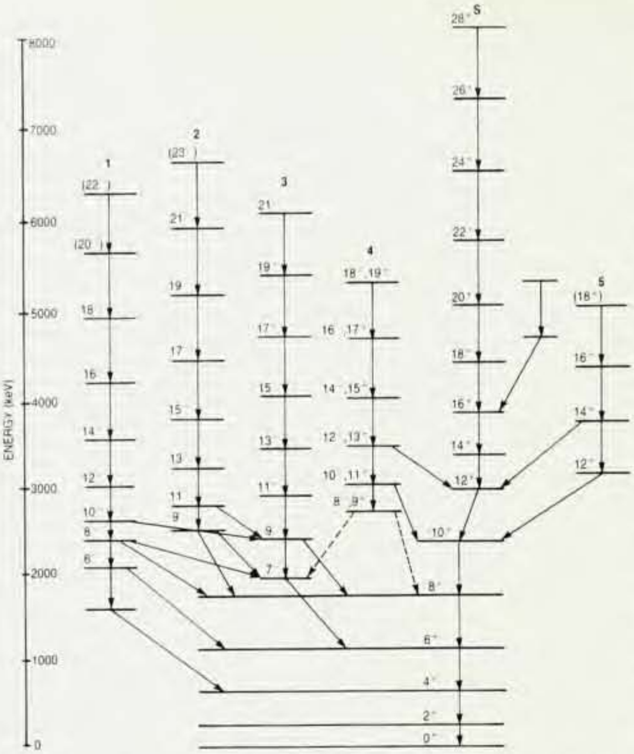
Probably the most spectacular advances in the last few years are in the realm of gamma-ray spectroscopy following heavy-ion fusion–evaporation reactions. Such reactions can be viewed semiclassically. Two nuclei collide and fuse; they subsequently emit several light particles—neutrons, protons and alphas—until the system has "cooled" sufficiently to emit gamma rays. During this "evaporation" process the nucleus loses only a little of the high angular momentum it acquires during fusion; the gammas are thus emitted from states with very high spin; these states are furthermore highly aligned along the beam direction. The alignment and the large fusion cross sections (hundreds of millibarns) makes the fusion–evaporation reaction a powerful tool for studying high-spin states. The "yrast" states (the states in a nucleus that have the lowest energy for a given angular momentum) are important because their wave functions are particularly simple—there aren't many ways of forming them—and thus reveal the underlying nuclear structure especially clearly.

An example of the way in which new techniques can be used to probe nuclear properties is the study of energy levels belonging to various rotational bands, such as those of ytterbium-161 investigated by Leo Riedinger and a group of colleagues using a tandem accelerator in Oslo, Norway.[6] The Yb^{160} was formed from a fusion of O^{16} and Sm^{147} nuclei, after three neutrons evaporated. These studies were subsequently continued at Oak Ridge, where the Yb^{160} is formed from the fusion of Ti^{48} and Cd^{116} with the evaporation of four neutrons. To determine the spins and energies of the Yb^{160} nucleus, Riedinger and his collaborators measured the energies and intensities of the gamma rays emitted as the nucleus spins down. In the earlier experiments, spins up to $28\hbar$ were observed, and later, at Oak Ridge,



Energy levels of erbium-168 for several series of levels; each level is labeled with its value of J^{π}. The experimental values (left) are compared with the theoretical predictions (right) from an interacting-boson model. (Adapted from reference 5.) Figure 4

Spectrum of energy levels of ytterbium-160. The levels in each series are labeled with their J^{π} values. The diagram as shown here does not do justice to the precision with which the levels are known—in general to 0.1 keV; the intensities and energies of all the marked transitions have been measured.[6] Figure 5



Riedinger has reported the yrast band out to states with J^{π} of 38^{+} or 40^{+}; the group has also seen states in other bands with spins as large $33\hbar$. Figure 5 shows the energy-level diagram that has come from these studies.

The states seen in such experiments cluster clearly into a small number of bands—each corresponding to a single cascade—which makes the analysis considerably easier. An ordinary energy-level diagram of Yb^{160} would show only an impenetrable thicket of states, and it is only recently that the new techniques and the experimenters' ingenuity have been able to pick out the specific states that show the simple band structure. Perhaps we should expand the Bohr–Mottelson rule on specificity to include detectors and computer analyses as well as the probes.

From the rotational band structure—such as one obtains from the gamma-ray cascade measurements—one can compute the moment of inertia of the nucleus as a function of energy. In some cases, it turns out that at particular values of J the nucleus has a smaller moment of inertia, and thus a slower rotational speed, than for neighboring states. For the yrast states of Yb^{160} this angular speed is about 0.27 MeV/$\hbar$. This phenomenon, called "back bending," is associated with a basic change in the band structure.

The linear polarization of gamma rays gives information on their multipolarity, that is, whether magnetic transitions, electric transitions or a mixture of both are involved. Because the polarization is proportional to the alignment of the nuclei, highly aligned states—such as those encountered in fusion–evaporation reactions—are very suitable to study multipolarity.

A simple polarimeter consists of two germanium detectors at roughly 20 cm from a target and the computer software to add their two signals if they are in coincidence; one thus measures the Compton scattering from one detector to the other. Compton scattering is sensitive to linear polarization, so the difference in the counting rates—that is, the difference in the Compton scattering perpendicular and parallel to the reaction plane—is a measure of the polarization. A computer automatically rotates the two-detector system at chosen intervals and stores the spectra. Figure 6 illustrates the results produced[7] by such a system.

A major advance in high-spin studies is the development of "inclusive" detection equipment, which strives to detect as many emitted particles and gamma rays as possible. Such "4π segmented detection systems" (so called because they cover a solid angle of nearly 4π steradians and because the individual detectors cover the sphere in segments, giving the system the appearance of an inverted fly's eye) allow measurements of the total energy and of the multiplicity of outgoing channels, and these parameters provide very selective signals for the isolation of different events. Examples of such detectors are the spin spectrometer at Oak Ridge, used, for example, in Riedinger's Yb^{160} studies, the similar Crystal Ball Spectrometer at Heidelberg and Tessa II at Daresbury,[8] diagrammed in figure 7. One of the very latest advances in gamma-ray detectors, incorporated in Tessa II, is to use bismuth germanate, instead of the standard scintillator, sodium iodide; bismuth germanate has about twice the density of NaI and thus allows smaller detectors for a given total efficiency.

Exotic nuclei

All the technical improvements alluded to in this article are applicable to the search for new isotopes. Techniques currently being pursued include the transfer of exotic clusters such as in the $Ne^{20}(He^{4},He^{8})Ne^{16}$ reaction we discussed earlier, in spallation of nuclei by high-energy protons (energies above 1 GeV); and in fusion–evaporation reactions with exotic targets or projectiles. Detailed spectroscopy of the gamma decay of new isotopes formed in the fusion–evaporation reactions can often provide valuable matrix elements for comparison with theory. For instance, in the last ten years, various groups at Brookhaven have observed gamma decays from 16 new isotopes. One interesting possibility is the production of O^{22} via $Be^{10}(C^{14},2p)O^{22}$, in which both target and beam are radioactive.

An important example of the application of the new spectroscopic techniques is the probable discovery[9] of the as yet unnamed element 109, which was formed via the $Bi^{209}(Fe^{58},n)109^{266}$ reaction. Actually, the α-decay of only one atom was observed in the course of three weeks, yet the experimenters can rather confidently associate this decay with 109^{266}.

Fundamental phenomena

The nucleus has played a central role in our understanding of the elementary particles and the forces and symmetries that govern them. For instance, most of the basic properties of the weak interaction were established from observations on β-decay in complex nuclei. A good example is the determination of the helicity of the neutrino by Maurice Goldhaber, Lee Grodzins and Andrew Sunyar in an elegant experiment that relied on a very detailed understanding of the spectrum of Eu^{152}. An example of current interest is nonconservation of parity in strong interactions.

In current fundamental theories, the nucleus is composed of nucleons and a meson field or, alternatively, of quarks (confined, as in the bag model) and a nonlinear meson field.[10] In nuclear physics there are several effects in which meson exchange between two nucleons can conceivably be isolated. Parity nonconservation—in which the Feynman diagram for the decay has one weak and one strong vertex—is one of these. The parity-changing force, expanded in **L·S** coupling, has six terms. To determine all six, one is led[11] to consider parity mixing in light nuclei whose structure is conceivably simple enough to be understood and isolated from the effect to be measured. The strength of this parity-changing force is on the order of 10^{-9} times that of the strong force, so the experiments are very hard indeed. We mention these considerations here to point out that one must determine the spectroscopy of the relevant levels with great precision and carry out the structure calculations with extreme care and thoroughness before the experimental data can produce a meaningful result. Such considerations have been a strong stimulus towards better shell-model calculations and more detailed and accurate measurements.

Applications

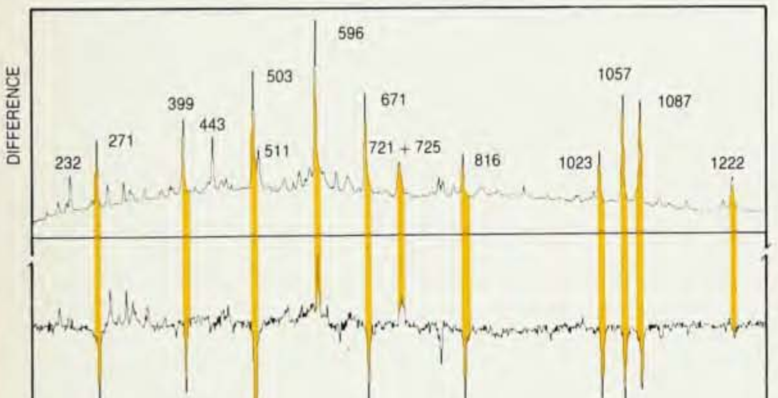
Our knowledge of nuclear spectra is also of importance in many other scientific areas: we shall mention only a few examples, in areas ranging from astrophysics to nuclear medicine.

Neutrinos from the Sun are believed to result primarily from the so-called pep reaction

$$p + e^- + p \rightarrow H^2 + \nu,$$

from K-capture in Be^7 and from the positron decay of B^8. Ray Davis, in several beautiful experiments, has found that the rate of neutrino detection is four times smaller than the predicted rate. For the past few years, some of the most interesting work on the light nuclei has been designed to elucidate this problem by remeasuring old values of cross sections, such as those for the reactions $Be^7(p,\gamma)B^8$ and $He^4(He^3,\gamma)Be^7$, and branching ratios. Often the location of an excited state becomes important: If a 0^+ state existed in Be^6 near the threshold for decay into $He^3 + He^3$, there would be less Be^7 formed in the proton chain, and the neutrino rate would decrease—compare the reactions $He^3(He^3,2p)He^4$ and $He^3(\alpha,\gamma)Be^7$. When this suggestion was made, a number of experimental studies quickly showed that no such state existed either in Be^6 or in the isobaric nuclei He^6 (the mirror nucleus of Be^6) and Li^6. We should add that the mystery concerning the flux of neutrinos from the Sun has not yet been solved.[12]

Nucleosynthesis in stars. Element production in early stars results in the conversion of hydrogen to helium through well-known chains of nuclear reactions.[13] In older stars, where heavy elements are present, the production of these must have involved chains of nuclear reactions that bypass the unstable nuclei whose atomic number is 5 (for instance, neither $He^4 + n$ nor $He^4 + p$ form stable entities), and reactions that cope with the slight instability of Be^8, which decays to two α particles. It is possible to detour around $A = 5$ via the $He^4(He^3,\gamma)Be^7$, $He^4(t,\gamma)Li^7$ and $He^4(d,\gamma)Li^6$ reactions. The problem of the instability of Be^8 is not severe. There are so many nuclei in a star that, while the mean lifetime of the Be^8 ground state is only 0.1 fsec, at any given time the star will contain a considerable number of Be^8 nuclei, formed from the collisions of α particles; these will be able to interact with α-particles to form C^{12} nuclei. The 0^+ state in C^{12} at 7654.2 keV is about 300 keV above the binding energy of $Be^8 + \alpha$ in C_{12}, and the tail of the 7.7-MeV state permits the reaction $Be^8 + \alpha \rightarrow C_{12}$ to proceed in red giant stars.[14,15] Beyond $A = 12$, the way is clear for the buildup of heavier elements.



Gamma-ray polarization spectra produced in the collision of 60-MeV ions of O^{18} on a thin foil target of Ge^{74}. The energies of the gamma-ray lines are indicated in keV; most of the lines are due to Zr^{88}, which is produced from the fusion of the nuclei with emission of four neutrons. To measure the polarization, two Ge(Li) counters were used, one counter detecting photons Compton-scattered in the other. Because Compton scattering depends on polarization, the difference in rates for the counters arranged in the reaction plane or perpendicular to it is a measure of polarization. The upper graph plots the sum of the two counting rates, the lower, the difference. With the convention used here, E2 transitions ($\Delta J = 2$) have negative values of the difference, M1 transitions ($\Delta J = 1$) have positive values. Figure 6

Gamow–Teller states and supernovae. Beta decay plays a pivotal role in the collapse of the stellar cores in supernova explosions. In particular, the rate at which neutrons can be formed from protons and electrons (an inverse beta decay), and thus the rate at which the pressure exerted by electrons can be removed during the collapse, is an important parameter of the collapse. One of the important processes that affects this rate is the Gamow–Teller transition, in which the spin of the nucleus changes by 1 unit. The location and strength of the Gamow–Teller resonances is thus an important part of the collapse problem.[16]

A group at Los Alamos has recently begun investigating manganese-56, using the (t,He^3) reaction, to locate the Gamow–Teller resonances and measure their strength. In these experiments we have been able to locate and study the few (16) 1^+ states in a dense sea of more than a hundred other states.

Fusion of light ions. The emphasis in the work on nuclear fusion as an energy source has been on reactions in which a neutron is involved as either the incident or the emitted particle. Among these are the reactions $H^3(d,n)He^4$, which liberates 17.6 MeV, $Li^6(n,\alpha)H^3$, which releases 4.8 MeV, and $H^3(t,2n)He^4$, which produces 11.3 MeV. While the cross section of neutrons on Li^6 is well known, the relevant cross sections for the other two reactions are poorly known in the regions that are of interest in the design of fusion reactors. Nelson Jarmie of Los Alamos has pointed out[17] that the present uncertainties in the d–t cross-section data may give rise to systematic errors of as much as 50% in the reactivity values. New measurements are therefore underway to determine absolute values of the cross sections for fusion reactions in the range 1 keV to 100 keV.

Dating and impurities. The properties of certain of the light nuclei have been used in such fields as radioactive dating and the determination of impurities in material samples. Carbon-14 dating, for example, has a long and successful history; more recently other isotopes, such as beryllium-10 with a 1.6-million-year halflife, have become useful in dating samples.

To search for impurities, one can use the well-known gamma-ray spectra of the light nuclei as standards. For instance, an impurity of fluorine-19 in a sample can be determined by bombarding the target with low-energy protons and looking at the γ-ray spectra for the well-known transitions in O^{16} from the $F^{19}(p,\alpha)O^{16}$ reaction.

Nuclear medicine. The applications of nuclear spectroscopy to nuclear medicine are numerous. (See the articles by John Laughlin and by Paul Moran, Jerome Nickles and James Zagzebski, PHYSICS TODAY, July, pages 26 and 36.) We shall mention one example. The spin-$\frac{1}{2}$, negative-parity state Tc^{99m} is an isomeric state; the ground state of Tc^{99} has a J^{π} of $\frac{9}{2}^{+}$. The isomeric state decays via a 143-keV gamma ray, with a halflife of 6 hours. A patient is given an intravenous injection of a compound that contains Tc^{99m} and that attaches itself preferentially to cancerous cells. After this compound has had time to go through the body, the patient is scanned by an array of NaI gamma-ray counters to determine if any part of the bone system shows an unusual intensity of γ-rays. Clearly, an unusual intensity can indicate a cancerous growth. There are, of course, scores of other ways in which nuclear spectroscopy, nuclear detectors and nuclear accelerators are of great benefit in diagnosing and treating patients for a variety of illnesses.

Future trends

To conclude this brief survey of recent progress, we try to suggest a few of the directions nuclear spectroscopy might take in the next few years.

▶ There will be studies of nuclear reactions involving beams or targets of radioactive nuclei; these will preferentially excite nuclear states that have not been seen (or have been inadequately studied) with present beams. For instance, an intense C^{14} beam with maximum energy near 108 MeV has just now been put into routine operation at Brookhaven.

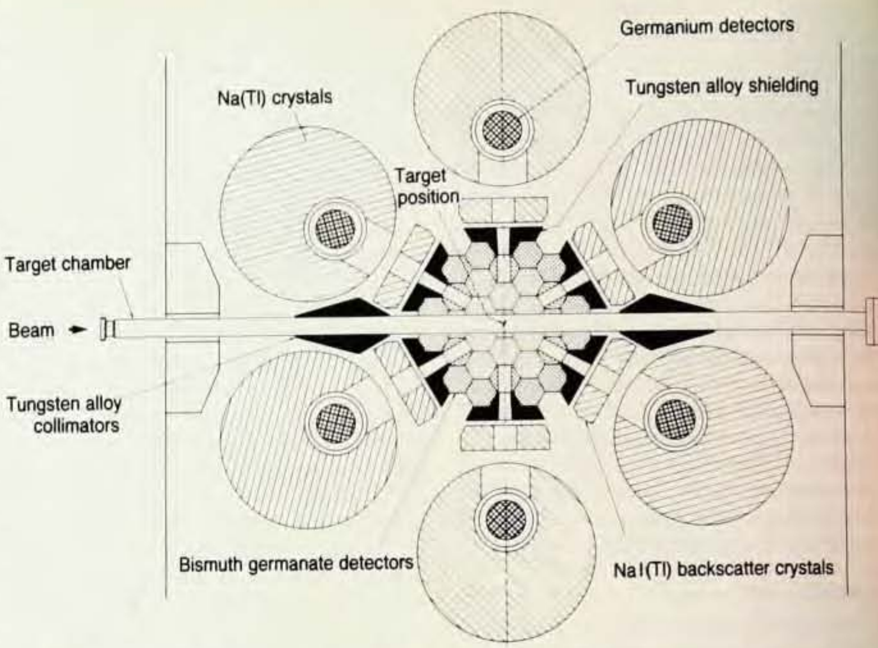
▶ Technical advances will continue in beam optics and in the detection of a wide array of outgoing particles with high efficiency and high resolution. These will permit us to resolve states more closely spaced than heretofore and to study states whose parameters are such that the cross section for forming them are very low.

▶ High-energy probes will be used much more widely. These will allow us to study nuclear degrees of freedom and the constituents of nuclei with greater accuracy and in new ways.

▶ Reaction mechanisms will be better understood when one knows with certainty the properties of the states involved in nuclear reactions.

▶ Nuclear models will gain in predictive power.

▶ More and more inclusive experiments will be done in attempts to measure all relevant parameters; the experiments will become more and more complex and more and more costly in both time and money. Thus the traditional distinctions between high-energy (elementary particle) and low-energy (nuclear) physics will dissolve.



TESSA II, a spherical spectrometer built at Daresbury in England. The diagram shows a vertical section through the center line. The outer germanium detectors are surrounded by NaI(Tl) crystal detectors to suppress the effect of Compton scattering. The central detectors are made of bismuth germanate. Figure 7

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