Physics with polarized nuclei

Recent advances in technique have greatly increased the scope of possible studies, including tests of fundamental symmetries and the spin dependence of nuclear forces.

William J. Thompson and Thomas B. Clegg

All those who wear Polaroid sunglasses are familiar with the polarization of light by reflection, a phenomenon first investigated by Etienne Malus in 1808 when he looked through a calcite crystal at the light reflected from the windows of the Palais Luxembourg. In 1921 Otto Stern and Walther Gerlach demonstrated the spin polarization of atomic beams in magnetic field gradients, and their methods are now in fairly widespread use.

Polarization of atomic nuclei is much harder to observe. Early nuclear polarization experiments, starting with those in Berkeley in 1951, investigated the spin dependence of the nucleon–nucleon interaction and the relation between spin–orbit coupling in scattering and in the nuclear shell model of bound states. Since the late 1960's the use of nuclear polarization has diversified greatly.

Recent advances in polarization techniques have greatly increased the versatility of studies that use spin-polarized nuclei. Among other uses, such techniques provide tools for testing fundamental symmetries and investigating spin dependence in the strong interaction, for simplifying nuclear spectroscopy, for measuring magnetic and electric moments of unstable nuclei by nuclear magnetic resonance (see figure 1), and for understanding reaction mechanisms in the scattering of nuclei by heavy ions.

How are polarized beams and targets produced, and how are they used? We address these questions emphasizing recent discoveries involving particle beams with energies ranging from 1 to 50 MeV.

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It is difficult to produce nuclear polarization. To understand why, consider an ensemble of particles with magnetic moments μ and spins s in thermal equilibrium at absolute temperature T. For magnetic-dipole interactions in a magnetic field B, the numbers of particles $N(m)$ in the various magnetic substates m are related by

$$N(m+1)/N(m) = \exp(\mu B/skT) \quad (1)$$

(k is the Boltzmann constant.) For protons in the Earth's field at room temperature, the spin-up and spin-down substates differ in population by about 4 parts in 10^{10}. However, a polarized beam or target is not practicable unless population differences of at least 20 percent are obtained. The difficulty of producing nuclear polarization is partly caused by the very small values of nuclear magnetic moments, which are much smaller than atomic magnet moments because of the small electron–proton mass ratio. Thus, even if an ensemble of atoms has been polarized, the polarization of their nuclei may still be difficult.

Notation

A special notation helps identify and characterize polarization experiments. An experiment whereby projectile particles a, with known polarization states hit a target nucleus A, to produce particles b and B (the latter usually not observed) is denoted by $A(\vec{a},b)B$.

Polarization observables of nuclei in a beam or target can be characterized by several parameters:

- Vector polarization has three components; for example the component P_z along a quantization axis z is given by

$$P_z = F_+ - F_- \quad (2)$$

where F_+ and F_- are the fractions of particles with spins parallel and antiparallel, respectively to that axis. For spin-½ particles, such as protons, neutrons, tritons (H^3 or t) and helions (He^3), P_z completely describes the polarization with respect to the z-axis.

- Tensor polarization, often called "alignment," is required for particles with spin $s \geq 1$. For $s = 1$ there are three independent polarization components of a second-rank tensor of which the simplest, P_{zz}, is

$$P_{zz} = 1 - 3F_0 \quad (3)$$

where F_0 is the fraction of the particles with spin components transverse to the z axis (the substate $m = 0$). Thus, $P_{zz} = 1$ if the system is completely a mixture of parallel and antiparallel spin projections, as for photons.

- Analyzing powers indicate the effect on cross sections of changes in the polarization of the beam or the target. For a polarized beam they describe the difference between $A(\vec{a},b)B$ and $A(a,b)B$. Each polarization component has its corresponding analyzing power, which characterizes the spin dependence of the interactions in a model-independent way. With the advent of polarized-ion sources, experiments to determine analyzing powers have become the most common in polarization physics.

- Polarization transfers measure the transfer of polarization from the initial system to the products of a nuclear reaction. For example, $A(\vec{a},\vec{b})B$ indicates measurement of polarization transfer from a to b. In early polarization studies the depolarization parameter was used as a measure of polarization transfer.

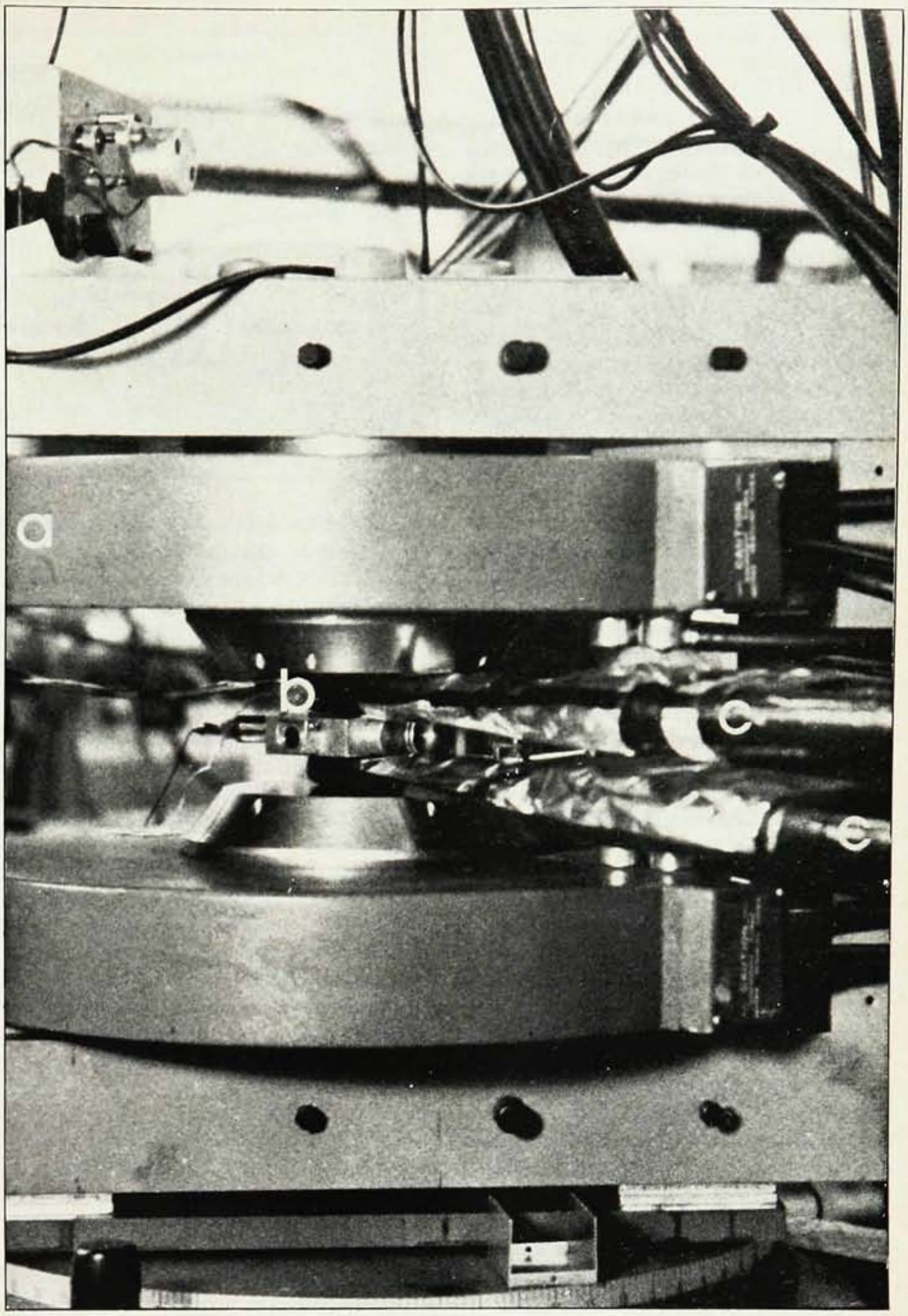
Polarized beams

Polarized beams were first produced by nuclear scattering. For example, protons scattered from helium-4 nuclei emerge completely polarized at some energies and angles because of spin–orbit coupling. A superior method used nowadays is to produce polarized beams in ion sources and then to accelerate the ions to the required energy. One of the advantages of this technique is that the beam intensity and quality are better than with other methods, which permits faster experiments with lower backgrounds than the earlier methods. By 1965 beam intensities of 10^{-5} microamperes were available at the target, but intensities of 0.1 microamp are now routine and 1 microamp will certainly soon be achieved. Another advantage of polarized beams from ion sources is that they provide flexibility in the type of polarization and spin orientation, since these parameters can be changed rapidly and reproducibly and can be accurately monitored.

Polarized-ion sources are of two basic kinds: the atomic-beam type and the Lamb-shift type. Atomic-beam sources, installed in about 25 laboratories worldwide, use Stern–Gerlach separation of the magnetic substates in a neutral atomic beam (figure 2). A discharge produces the atomic beam, which then passes through an inhomogeneous field produced by a sextupole magnet. The atoms emerge from the magnet polarized in electron spin. These neutral atoms then undergo hyperfine transitions in an rf field to produce the desired nuclear polarization. Finally, the atoms are ionized in a strong magnetic field and injected into an accelerator. Polarized H^+ beams of 15 microamps have been achieved in several laboratories. Such beams are usually accelerated in cyclotrons, where substantial beam losses occur, providing a maximum of about 0.3 microamp accelerated beam.

Atomic-beam sources are also used to produce polarized beams of negative ions for use with tandem Van de Graaff accelerators. Until recently this has been accomplished only by charge exchange of polarized beams of positive ions in sodium vapor, which yields a polarized negative-ion beam of about 0.3 microamp before acceleration. At the University of Wisconsin it has recently been shown that direct conversion of the polarized, thermal, atomic beam to negative ions is possible also by charge exchange with a fast (about 40 keV), neutral cesium beam. This technique has already produced 3 microampere beams of polarized H^- or D^- and should soon lead to accelerated beams of at least 1 microamp for tandem accelerators.

An atomic-beam polarized ion source for alkali-metal ions has been developed at the University of Hamburg and the Max-Planck Institut für Kernphysik in Heidelberg. Vector- and tensor-polarized beams of Li^6 ($s = 1$) and Li^7 ($s = 3/2$) have been produced with 0.1 microamp intensity. For Li^6 the polarizations are nearly the theoretical maxima for the polarization scheme used ($P_z = 2/3$ and $P_{zz} = 1$), while for Li^7 $P_{zz} = \pm 0.4$ is attained. Experiments with polarized beams of Na^{23} ($s = 3/2$) are also in progress.



Nuclear magnetic resonance measurements of magnetic moments of unstable nuclei can use a polarized beam to produce polarized β-unstable nuclei by nuclear reactions. The beam from an accelerator behind the magnet labelled **a** hits a target near the rf field probe labelled **b**. Beta detectors, above and below the target, measure the up–down asymmetry in the β-decay. The light pipes from the detectors are labelled **c**. (Arrangement as in reference 1) Figure 1

Lamb-shift polarized negative-ion sources are now used on about 15 tandem Van de Graaff accelerators. A Lamb-shift source (figure 3) produces a polarized beam from one-electron atoms in their $2S_{1/2}$ excited state. In zero magnetic field the $2S_{1/2}$ and $2P_{1/2}$ states are separated by the Lamb shift. In an external magnetic field these states are split (the Zeeman effect) and near 575 gauss there is a level crossing between magnetic substates. The resulting degeneracy permits one selectively to induce the admixture of $2S_{1/2}$ and $2P_{1/2}$ substates by magnetic and electric fields. Since the decay $2P_{1/2} \rightarrow 1S_{1/2}$ is an allowed electric-dipole transition, $2S_{1/2}$ atoms in three of the hyperfine states can be caused to decay rapidly, leaving the remaining $2S_{1/2}$ atoms in a single state, hence with pure nuclear polarization.

Practical sources based on the Lamb-shift principle require efficient production of the $2S_{1/2}$ atomic beam. For hydrogen this is done by charge exchange of an H^+ beam in cesium vapor and deflection of the H^+ and H^- ions emerging in the beam from the charge-exchange region. The nuclear-polarized $H(2S_{1/2})$

atoms must be ionized without producing unpolarized H^- ions from unpolarized $H(1S_{1/2})$ atoms in the beam. This is accomplished by selective charge exchange in argon. Polarized beams of H^- and D^- from Lamb-shift sources have attained 1 microamp and accelerated beams with one third this current have also been obtained.

The Lamb-shift technique has also recently been used for other one-electron atoms or ions. For example, at Los Alamos the first source of polarized tritons produces accelerated beams of 0.2 microamp with polarization of 0.85. At the University of Birmingham a $(He^3)^{++}$ beam of 5×10^{-4} microamp and a polarization of 0.65 has been obtained. Developments underway are expected to increase both of these values.

Polarized neutrons are produced by removing them from nuclei using spin-dependent nuclear reactions. Collimated neutron beams with good energy resolution have relatively small fluxes of about 10^7 per second, a value 10^{-5} that of charged-particle beams in the same energy range. However, targets used for neutron bombardment may be 10^5 times thicker than with charged particles, because of the very small neutron energy-loss rate. Fortunately, the reactions commonly used for neutron production, $d(d,n)He^3$ and $t(d,n)He^4$ are very strongly spin dependent.

Thus, emerging neutron beams are often significantly polarized even without initial polarization in the system. Enhancement of the neutron polarization has been achieved by initiating the above reactions with polarized deuteron beams, since neutrons emerging along the incident beam direction often maintain predominantly the orientation they had in the incident deuteron. One can now typically achieve a given statistical accuracy in an experiment much faster using the neutrons from the $d(\vec{d},n)He^3$ or $t(\vec{d},n)He^4$ reactions than if these reactions are initiated by unpolarized deuterons.

The determination of the beam's polarization usually requires a nuclear polarimeter, a device that scatters some of the beam particles from a target for which the analyzing power has been accurately calibrated, as in $He^4(\vec{p},p)He^4$, $He^4(\vec{d},d)He^4$, and $He^3(\vec{d},p)He^4$. For Lamb-shift sources, application of an electric field of about 300 volts/cm in the ion source will cause decay of $H(2S_{1/2})$ atoms. The ratio of beam currents with and without this field can then be used to determine the beam polarization. Polarization is generally harder to measure for neutrons than for charged particles because, although the nuclear reactions used are no less spin dependent, the difficulties of detecting neutrons are much greater.

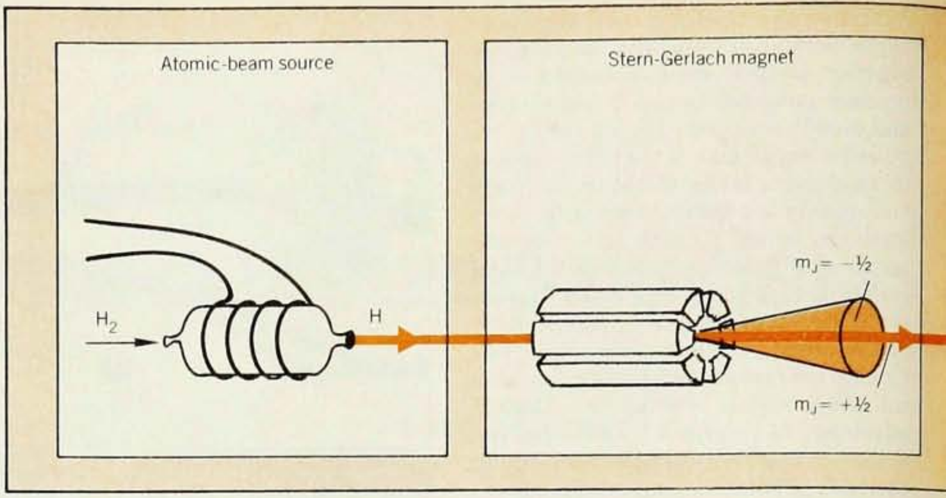
Polarized targets

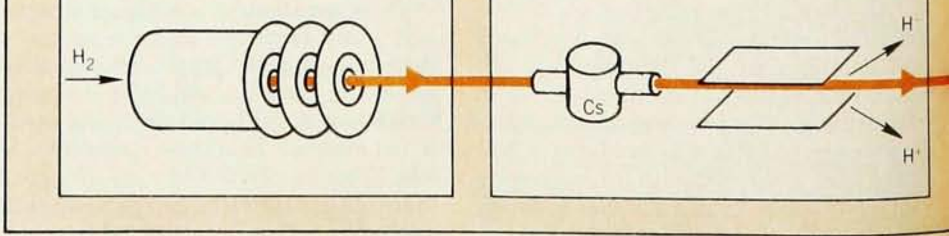
In studying interactions that depend on the spins of projectiles or target nuclei, use of a polarized target greatly enhances the effects of spin dependence. Recent technical advances have hastened the development of polarized targets. Room-temperature methods often use adaptations of polarized beam techniques. Thus, researchers at Stanford University and the University of Wisconsin have produced nuclear-polarized targets of hydrogen from atomic-beam jets using the discharge and sextupole sections of an atomic-beam polarized source. The targets have a polarization of 0.37 and a density of 2×10^{11} atoms/cm^3. Such an atomic-beam target may be possible for many halogen gases and for the alkali metals, and work in progress shows that the density of polarized target nuclei can be increased by confining the atoms to the neighborhood of the scattering region.

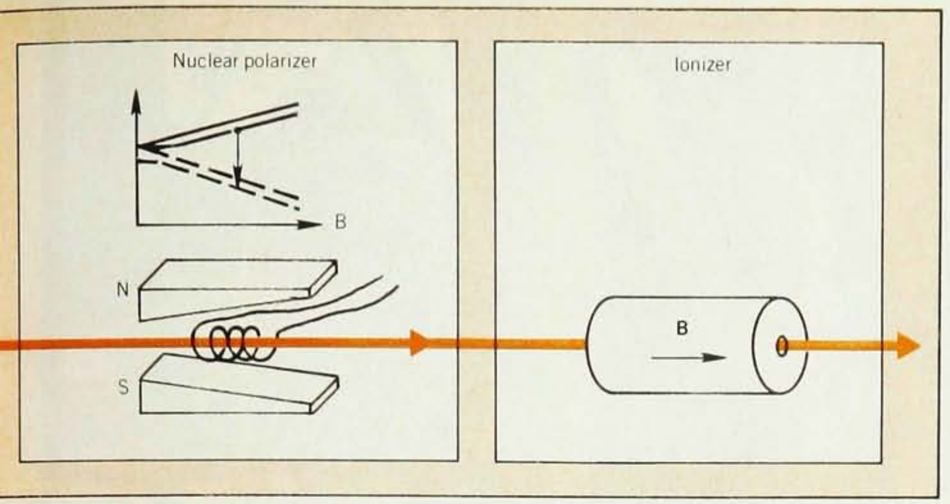
At the University of Hamburg, physicists have recently produced polarized Li^6 targets with polarization lifetimes of a fraction of a second and an average thickness of a few hundredths of an atomic layer. The technique used in these experiments involves the deposition of polarized Li^6 beams from an atomic-beam source onto a heated, oxygenated tungsten surface.

University groups in Basel, Hamburg, Houston (Rice), and Toronto have used optical pumping of He^3 to produce polarized He^3 nuclei. By irradiating He^3 in a Pyrex scattering chamber with circularly polarized radiation from a He^4 light source, they obtained polarizations greater than 0.20 at pressures between 0.1 and 10 Torr.

Other target polarization schemes employ cryogenic methods. These are based on the fact that reducing T increases the exponent $\mu B/skT$ in equation 1 and thereby increases the polarization. Typically, a large magnetic field aligns the atomic electrons, which, in turn, produce a field at the nucleus usually at least ten times larger than the applied field. Further, the availability of He^3–He^4 dilution refrigerators has made temperatures of 30–50 mK readily attainable in the targets for neutron beams. For charged particles with energies below 50 MeV, however, much energy is deposited in the target, so that maintaining the necessary low temperatures is more difficult. Nuclear-physics experiments at low energies have used low-temperature polarized targets of, for example, Co^{59} and Ho^{165}. Large magnetic hyperfine fields polarize these nuclei, whose magnetic moments are also large. Researchers at the universities of Groningen and Hamburg used a Co^{59} target in the apparatus shown in figure 4. With the increasing availability of superconducting magnets and dilution refrigerators, "brute-force" polarization by maximizing







A hydrogen atomic beam source. The beam source dissociates hydrogen molecules to produce a thermal-energy jet of hydrogen atoms. These pass through a sextupole Stern–Gerlach magnet, which defocusses atoms with $m_J = -\frac{1}{2}$ and focusses those with $m_J = +\frac{1}{2}$. The resulting electron-polarized beam next passes through a region in which rf fields induce hyperfine transitions to polarize the protons, as illustrated in the energy-level diagram. Finally, the atoms are ionized by electron bombardment to produce polarized H^+ or by charge exchange with cesium to produce polarized H^-. The polarized ions are then accelerated. Figure 2

B/T will probably become a feasible method for a wide variety of nuclei.

Other polarization methods are applicable to hydrogen and deuterium targets and are used in high-energy physics. Some of these techniques are adaptable to lower energies, if effects from target heating are overcome. In one scheme "frozen-spin" polarized-proton targets are prepared adjacent to the target area, where the target material in an organic host is exposed to microwave pumping at an electron-spin resonance frequency, producing the desired polarization. Experiments using this technique have attained fairly stable polarizations of 0.95 and 0.40 for protons and deuterons, respectively.

Another target polarization technique, perhaps adaptable to lower energies, is based on the transfer of paramagnetic-ion polarization from ions that are highly anisotropic magnetically (such as ytterbium in Yb-doped Y-ethylsulfate crystals) to the proton spins by rotating the crystal at 100 to 200 Hz relative to a field of 10 kG at 1.3 K. Such a "spin refrigerator" developed by a group at the University of Massachusetts does not require a uniform magnetic field and gives a proton polarization of about 0.80 after half an hour of rotation. When the rotation is stopped the polarization decays with a relaxation time of several days.

Several elegant experiments with polarized nuclei are testing the basic symmetry operations of parity (reversal of space coordinates), time reversal, and isospin (charge symmetry) in the strong (nuclear) interaction.

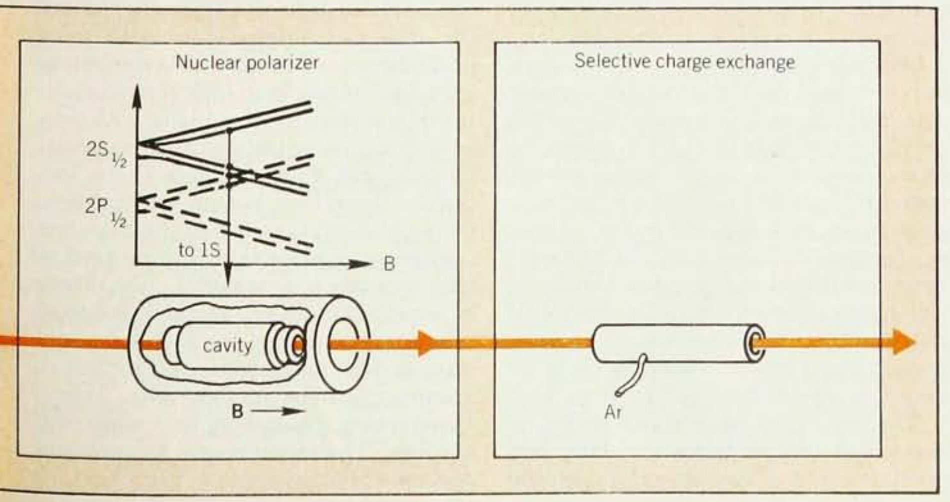
Parity conservation

Physicists at Los Alamos have investigated the conservation of parity in the strong interaction by placing limits on the difference between the total cross sections in proton–proton elastic scattering for beams polarized parallel and antiparallel to the direction of motion (longitudinal polarization). Extreme care must be taken in such experiments to ensure that the only variable in the experiments is the reversal of longitudinal polarization; for example, no significant shift in the beam's position or reversal of transverse polarization may occur. At an energy of 15 MeV, the longitudinal analyzing power is -2×10^{-7} or less, a value consistent with theoretical models in which parity nonconserving terms arise from the presence of weak-interaction currents in nuclei.

Another basic experiment detects parity mixing by investigating the presence of both electric and magnetic transitions of the same multipolarity between the same two nuclear energy levels. A group at the University of Washington is studying such mixed-parity transitions by measuring the net left–right asymmetry of the gamma rays from the decay of the 110-keV level of polarized F^{19} nuclei, produced by $Ne^{22}(\vec{p},\alpha)F^{19}$. The results now suggest that explanations of the parity violation based solely on weak-interaction charged-current (Cabibbo) models is ruled out.

Other possible effects in which parity is not conserved in the strong interaction are being studied in a collaboration between Stanford University and Argonne National Laboratory with the reactions $\vec{Li}^6(He^4,\gamma)B^{10}$ or $He^4(\vec{Li}^6,\gamma)B^{10}$ near the 5.166-MeV, spin $J = 2$, positive-parity (or $J^\pi = 2^+$), isospin $I = 1$ level in B^{10}. This state lies close to another in B^{10} with $J^\pi = 2^-$, $I = 0$, which would enhance those effects of parity mixing arising from interactions that change isospin by one unit. The charged-current (Cabibbo) version of the theory of weak-interactions predicts a vector analyzing power of 2×10^{-4} for this reaction, while a calculation based on the neutral weak-interaction current (Weinberg–Salam) version predicts 4×10^{-3}.

The breaking of time-reversal symmetry has been inferred only in the decay of the neutral K meson. Searches for violation of time-reversal symmetry in low-energy nuclear phenomena with polarized systems have involved testing for differences between $A(\vec{a},b)B$ and $B(b,\vec{a})A$.



A Lamb-shift source for hydrogen. The positive-ion source produces a proton beam of about 500 electron volts. The protons then enter a charge-exchange canal where a substantial fraction are converted (by charge exchange with cesium) to neutral hydrogen atoms in the metastable 2S state. An electric field sweeps out the ions from the beam. The nuclear polarizer uses dc and rf fields to induce decay of three of the four hyperfine levels, leaving the remaining H(2S) atoms in a nuclear-polarized state. Selective charge exchange in argon then produces the desired H^- beam from the polarized H(2S) atoms, leaving H(1S) un-ionized. The cover shows the positive-ion source and charge-exchange region (right to left). Figure 3

Differences of order 10^{-3} are predicted for various time-reversal non-invariant interactions, but the experimental arrangements for analyzing power and polarization measurements are sufficiently different that such accuracy has not yet been achieved.

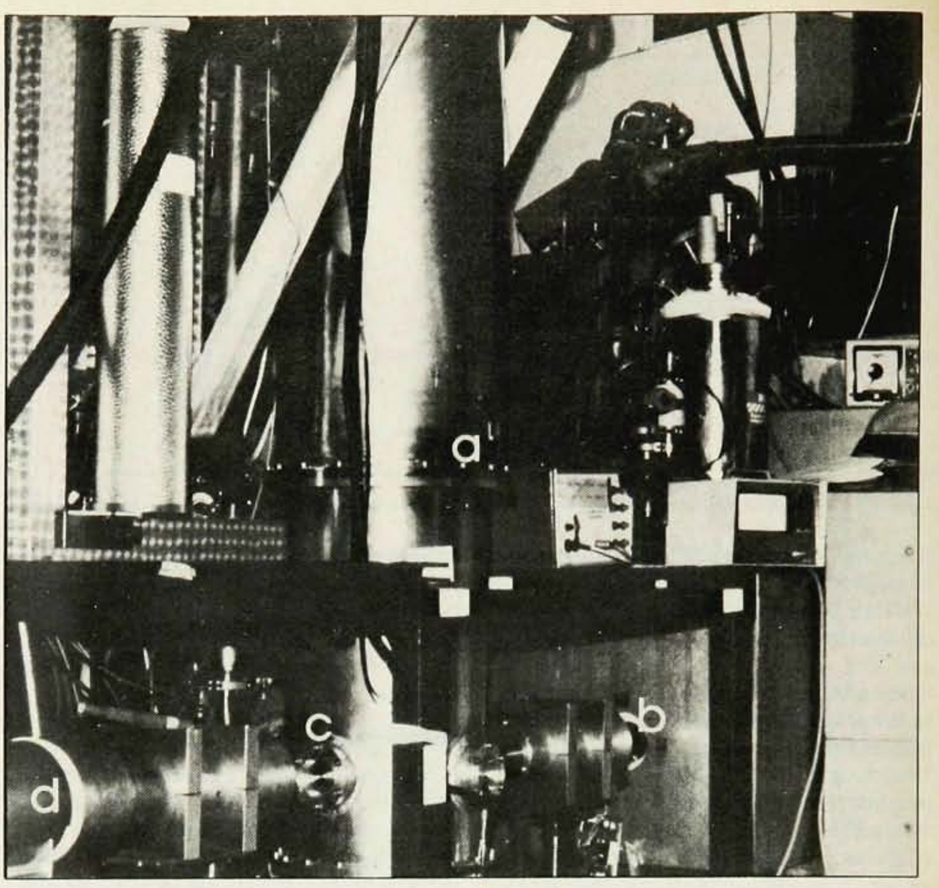
In the search for violations of time-reversal symmetry in the weak interaction, physicists at Princeton have recently polarized Ne^{19} by the $F^{19}(p,n)\,\tilde{N}e^{19}$ reaction. By studying the angular distribution of the reaction products in the decay $\tilde{N}e^{19} \rightarrow F^{19} + \beta^{+} + \nu$ they found that terms of the form $\mathbf{P}\cdot(\mathbf{v} \times \mathbf{q})$, where $\mathbf{P}$ is the $\tilde{N}e^{19}$ polarization and $\mathbf{v}$ and $\mathbf{q}$ are the direction vectors of the positron and neutrino respectively, constitute only a fraction of between 5 and 15 parts in 10^4 of all the decay events. This result is consistent with electromagnetic effects that are invariant under time-reversal and that arise from scattering of the positron from the daughter nucleus.

The investigation of charge symmetry in the strong interaction can take place only in the presence of the symmetry-breaking Coulomb interaction for protons. Researchers have attempted to test charge symmetry in light nuclei by comparing charge-mirror nuclear reactions, such as $d(\vec{d},p)t$ and $d(\vec{d},n)He^3$, but there are no model-independent theoretical methods of removing the effects of the Coulomb interaction. Thus the question of the violation of charge symmetry in the nuclear interaction is not likely to be resolved by such experiments.

The most promising charge-symmetry test is that for the neutron–proton system. If charge symmetry holds, then the neutron analyzing power A_n in $p(\vec{n},n)p$ should be equal to the proton analyzing power A_p in $n(\vec{p},p)n$. Theory predicts a difference on the order of 3×10^{-3} between A_p and A_n at beam energies near 200 MeV and detection angles for maximum sensitivity, so that a high-precision experiment is required. Values of A_p and A_n can be extracted simultaneously from the experiment $\vec{p}(\vec{n},n)p$, which has been proposed by groups working at the Indiana University Cyclotron Facility and at the Tri-Universities Meson Facility in Vancouver.

Spin dependence in nuclear interactions

Data about the nucleon–nucleon interaction will, we hope, permit us to calculate the properties of systems involving a few interacting nucleons. The rich angular momentum structure of this interaction pervades the properties of all nuclei, and polarization data greatly aid in the interpretation of this structure. The status of the description of the nucleon–nucleon interaction by phase shifts or by model potentials is still not definitive, however, as demonstrated by recent, very accurate data from Triangle Universities Nuclear Laboratory for proton–neutron scattering experiments done with beams of 17-MeV polarized neutrons.



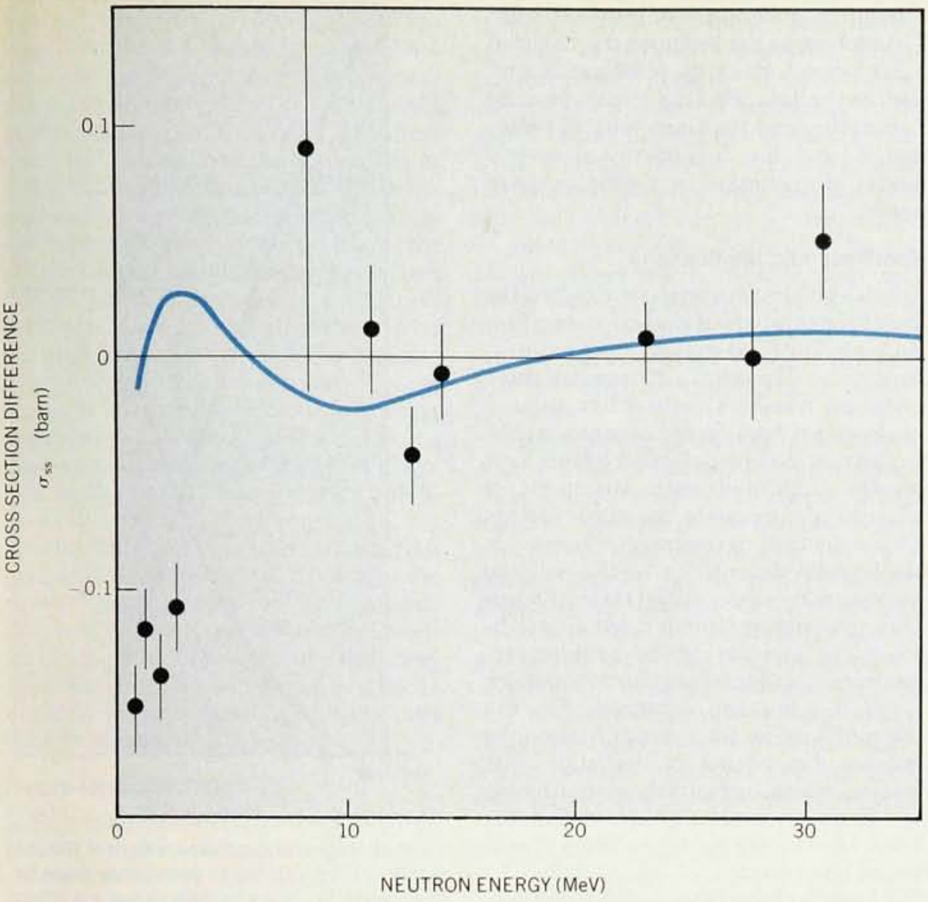
Polarized neutrons produced by nuclear reactions scatter from a polarized Co^{59} target held in a cryostat (the pipe labelled **a**) at 50 mK, in the field of a superconducting magnet. The neutrons come through the beam port (labelled **b**), pass through the target vessel (labelled **c**) and are detected at the end of the beam pipe (labelled **d**), to the left of the picture. This setup was used to obtain the data shown in figure 5. (Based on reference 2) Figure 4

An important topic in understanding nucleon–nucleus interactions is the average nuclear potential in which a nucleon moves. The spin-orbit part of this potential is written as $V_{so}(r)\mathbf{l}\cdot\mathbf{s}$ where r is the nucleon–nucleus separation, $\mathbf{l}$ is their relative orbital angular momentum vector and $\mathbf{s}$ is the nucleon spin. Spin–orbit coupling is essential to produce the shell structure observed in many nuclear properties. Is is now fairly well understood in terms of the nucleon–nucleon interaction, and its effect is generally computed as an average of the spin–orbit interaction between nucleons, taken over the density of nucleons in the nucleus.

This so-called "folding model" potential is peaked near the nuclear surface. Two developments have made refinement of this model possible. First, increased beam intensities from polarized-ion sources enable accurate analyzing-power data to be obtained for proton elastic scattering; and, second, accurate charge-density distributions from the analysis of electron scattering in the 100–800-MeV range allow determination of nuclear-density distributions, assuming the same densities for neutrons and protons.

The folding model produces very good agreement with polarization data, and predicts a peak of the spin–orbit potential at about 80 percent of the radius of the central potential. This is attributed to the short range of the nucleon–nucleon spin–orbit interaction, a result that is explained in meson field theory: comparatively short-range ω and ρ meson fields are presumed to mediate the spin–orbit force, while the much longer-range pion field propagates the major part of the central interaction.

The nucleon–nucleon interaction contains spin–spin terms that depend on the relative orientations of the nucleon spins and which produce the energy difference of about 2 MeV between the bound deuteron triplet state with spins aligned and the unbound singlet state with spins anti-aligned. One way of investigating spin–spin terms is to look for effects in nucleon scattering from nuclei with nonzero spin. Polarized nuclei are essential for two types of such studies: In the first, polarized nucleon beams are scattered from polarized targets and the change in scattering cross section with reversal of spin orientation is measured. The variety of target nuclei which have been polarized effectively and used for such spin–spin cross-section measurements is restricted. However, groups in Palo Alto, Tokyo, Groningen and Hamburg have made such studies. The experimental arrangement and data for studies of the $\vec{C}o^{59}(\vec{n},n)Co^{59}$



Scattering of polarized neutrons from polarized cobalt-59, as measured using the arrangement shown in figure 4. We show σ_{ss}, half the difference in total cross sections for spins polarized parallel and antiparallel, as a function of neutron energy. The theoretical curve is calculated from a representative spin–spin interaction model. (From reference 2.) Figure 5

reaction at neutron energies up to 30 MeV are shown in figures 4 and 5.

The second type of study investigating the spin–spin terms measures the depolarization parameter by scattering a polarized beam from an unpolarized target; the outgoing beam polarization is measured by a second scattering. Such measurements are practicable only for proton scattering, and their sensitivity to spin–spin effects is reduced by the random orientation of the target nuclei, so that the beam polarization changes only a few percent. The most recent data have been obtained at the University of Washington and at Berkeley for $Be^9(\vec{p},\vec{p})Be^9$, and at Los Alamos for $N^{14}(\vec{p},\vec{p})N^{14}$.

Elucidation of the theory of nucleon–nucleus spin–spin interactions has been difficult for three reasons. First, model calculations have averaged the spin–spin interaction between the projectile and the valence nucleons of the target nucleus over the bound orbits of these nucleons. The effective spin–spin interaction needed may be quite strongly modified from the free nucleon–nucleon interaction, since the two nucleons interact in the presence of other nucleons. Second, for non-spherical nuclei with $s > \frac{1}{2}$, effects depending on quadrupole moments can mask the spin–spin interaction. Third, as seen in figure 5, the data and theory disagree at the lowest bombarding energies, where effects from formation and decay of a compound nucleus predominate. At higher energies, the observable effects become very small and difficult to measure accurately. Therefore, further developments are needed to clarify the spin–spin interaction.

For loosely bound composite projectiles such as d, t, or He^3, a good approximation to the potential for their scattering might be the average of the nucleon–nucleus interactions over the nucleon motions within the projectile. In this folding model, the central potential has about the same shape as the nucleon potential, and a depth proportional to the number of projectile nucleons, a result which is consistent with cross-section data for elastic scattering. Polarized-ion sources for deuterons, tritons, and He^3 have allowed the folding-model predictions to be tested in greater detail. For example, the deuteron spin–orbit potential is predicted to have a radial dependence similar to that for nucleons and to be of about the same strength, because the two nucleon spins are parallel and each contributes, on average, half the orbital angular momentum. This prediction agrees well with data from elastic scattering of vector-polarized deuterons.

On the other hand, triton and He^3 spin–orbit coupling strengths are predicted to be about one-third of that for a nucleon, since two of the nucleons have their spins coupled to zero while the other carries only one-third of the linear and angular momentum in the mass-3 system. Accurate polarization data from Los Alamos for triton scattering indicate instead that the spin–orbit strength is about the same as that for nucleons, while less-extensive data obtained with polarized beams of He^3 at the University of Birmingham, also disagree with the folding model. The resolution of this puzzle should lead to new insights into the scattering mechanisms and structure of composite projectiles.

For the deuteron one can investigate those parts of the neutron-proton relative motion that have two units of orbital angular momentum (the D state) by studying the tensor analyzing powers for (d,p) reactions at bombarding energies well below the Coulomb barrier. Under these conditions the change in cross section with spin orientation is very pronounced, because the neutron approaches the nucleus much more closely when the deuteron spin (and hence its quadrupole moment and the D-state part of its wave function) is perpendicular to the direction of motion than when it is along it. At the University of Wisconsin, research on (d,p) tensor analyzing powers has produced results inconsistent with some proposed deuteron wave functions, as shown by the incorrect behavior of the ratio of D- to S-state components of the wave function for large neutron–proton separations. Other deuteron observables such as the binding energy, magnetic dipole moment, and electric quadrupole moment, are insensitive to this ratio.

The giant electric dipole ($E1$) resonance has been represented predominantly as a collective motion of nucleons in which the protons and neutrons oscillate separately about their center of mass. This motion gives rise to enhanced $E1$ gamma radiation in radiative capture reactions such as $A(p,\gamma)B$, where A is the target and B the final nucleus. The use of polarized protons in this reaction produced the first detailed knowledge of the configuration of the giant resonance. By using polarized incident beams one can change the total angular momentum projection of the system, enabling the investigation of the interference between the $E1$ component and other multipole components of the radiation. Since the (p,γ) cross section is typically two orders of magnitude smaller than that for producing nuclear particles, reliable results were obtained only when high-efficiency gamma-ray detectors and intense, highly polarized, proton beams became available. At Stanford University a study of $N^{15}(\vec{p},\gamma)O^{16}$ suggested the occurrence of giant electric quadrupole ($E2$) components similar to the $E1$ resonance but with

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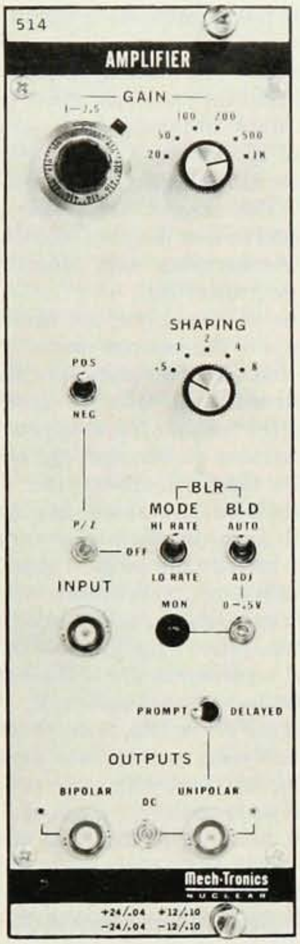

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a slightly different excitation energy. The technique has become established at other laboratories with polarized beams, such as the Triangle Universities Nuclear Laboratory and the University of Washington, and has helped reveal several modes of excitation in a wide range of nuclei.

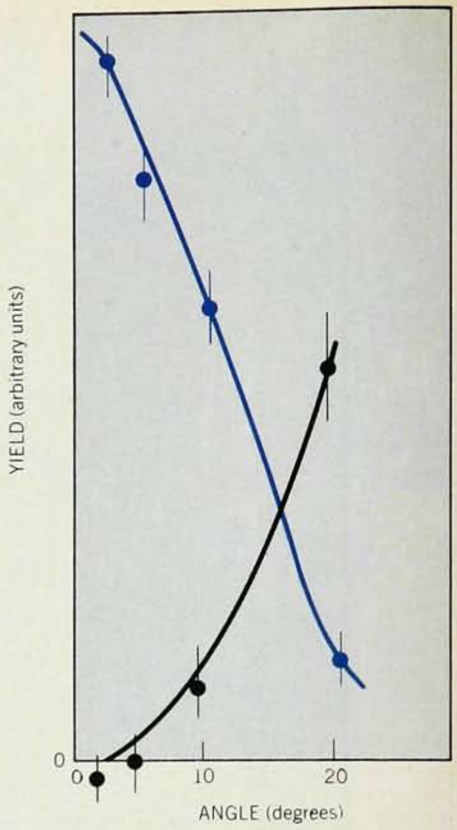
Spectroscopic applications

Nuclear spectroscopy establishes the quantum numbers of nuclear energy levels, including total angular momentum J, parity π, and isospin I. Changes of these quantum numbers occur when valence nucleons are transferred between nuclei. In the past decade polarized beams have greatly facilitated such spectroscopic studies. For example, the (d,p) reaction adds a neutron to the target nucleus. A shell-model description of the residual nucleus as the unperturbed target nucleus plus a valence neutron is often appropriate. The neutron orbital angular momentum l_n and total angular momentum $j_n = l_n \pm 1/2$ are then of interest. One can often determine the value of l_n from the angular dependence of the (d,p) cross section, which is relatively insensitive to j_n. However, a vector-polarized deuteron beam shows a strong dependence of analyzing powers on j_n.

Physicists have extended this method, developed at the Universities of Wisconsin and Birmingham, to other single-nucleon transfer reactions, to the two-nucleon transfer reactions ($\vec{p}$,t), ($\vec{p}$,He^3), ($\vec{d}$,α) and ($\vec{Li}^6$,α) to the three-nucleon transfer ($\vec{p}$,α), and to the "alpha-particle" transfer reactions ($\vec{d}$,Li^6) and ($\vec{Li}^6$,d). All of these reactions probe valence nucleon configurations. The multi-nucleon transfer reactions are particularly important in understanding correlations between nucleon motions in nuclei. Groups at Notre Dame, Munich, Triangle Universities, Los Alamos, Tsukuba, McMaster, Eindhoven and Heidelberg are pursuing this research.

A selection rule for completely tensor-polarized spin-1 beams ($P_{zz} = -2$) relates spins and parities of nuclear states. An example is the reaction C^{12}($\vec{d}$,α)B^{10} for a given energy level in B^{10}. The constraints of zero spin for the target nucleus, $P_{zz} = -2$ for the beam, rotational invariance of the Hamiltonian, and detection of the alpha particles along the beam axis, require that, of the $2J + 1$ magnetic substates m, only that with $m = 0$ is produced.

Symmetry conditions then give a model-independent selection rule: For a final state with parity π, the on-axis (d,α) cross section for a fully tensor-polarized deuteron beam is zero if $\pi = (-1)^J$. As figure 6 shows, the $m = 0$ yield for a $J^\pi = 2^+$ state is zero, while that for a $J^\pi = 2^-$ state is not zero. Groups at McMaster University and at the ETH in Zürich have demonstrated the power of this polarization technique.



Yield of magnetic substates with $m = 0$ in the reaction C^{12}(d,α)B^{10} at an emergence angle for alpha particles close to zero shows the effect of a spin–parity selection rule. For a level with total spin J the yield of the $m = 0$ substate vanishes at zero angle for a final state in B^{10} with parity $\pi = (-1)^J$, as for $J^\pi = 2^+$ (black curve), but is generally non-zero if $\pi = (-1)^{J-1}$, as for a $J^\pi = 2^-$ state. (Based on ref. 3) Figure 6

Magnetic dipole moments μ and electric quadrupole moments Q of excited states are of great interest for nuclear structure. Since the majority of nuclear ground states are short-lived, their electromagnetic moments cannot be determined by conventional atomic spectroscopic methods. The fact that β-decay violates parity conservation allows the polarization of the parent nuclei to be deduced from the directional asymmetry of the β emission. If the parent nuclei are in a host material, external magnetic fields are needed to establish a quantization axis. However, if one superimposes a variable-frequency field, the nuclear spins will be flipped and the polarization destroyed when the nuclear magnetic resonance (nmr) frequency is reached, thus giving a measure of the magnetic moment.

Polarization of the parent nucleus can be produced by a reaction with an unpolarized beam, by an ($\vec{n}$,γ) reaction with slow neutrons, or, as achieved at Stanford University, by using polarized charged-particle beams to produce polarization transfer to the parent nucleus. For example, researchers used Li^7($\vec{d}$,p) Li^8, followed by β-decay to Be^8, with the equipment shown in figure 1 to produce the nmr spectra shown in figure 7. Here, however, the magnetic-moment transition is split into four separate transitions because the electric quadrupole moment Q of the Li^8 interacts with the crystal field of the hexagonal $LiIO_3$ used as a host material. This allows determination of $|Q|$ for this unstable nucleus. Such experiments have become practicable and are versatile for two reasons. First, the polarization of the incident beam is high and polarization transfer to the parent nucleus is large, even when averaged over the angles of the recoiling Li^8 nuclei and over all energies of the beam, which stops in the thick target. Second, moderate external holding fields (~5 kG) can be used to maintain the precessional direction of the parent nuclei during the β-decay lifetime.

Solid-state relaxation processes, which gradually deplete the polarization of the parent nuclei in the host material, provide information about magnetic interactions within the host. For example, the relaxation time for Li^8 implanted in lithium metal by recoil is an order of magnitude shorter than in a $LiIO_3$ crystal.

Heavy-ion polarization

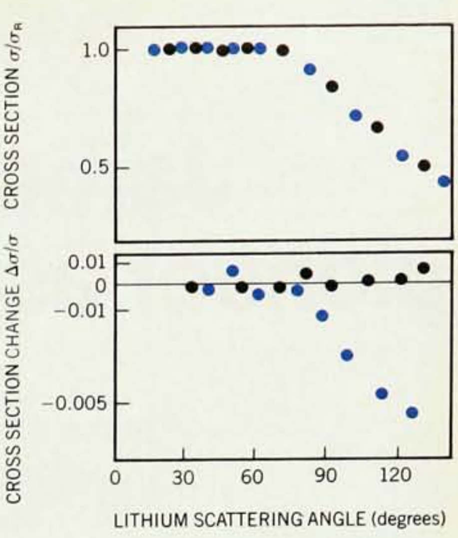
Spin-dependent effects for heavy ions ($A > 4$) are receiving increased attention, as several recent investigations have shown. Spin–orbit coupling for $\vec{L}i^6$ elastic scattering has been studied in experiments at the Max-Planck Institut für Kernphysik in Heidelberg. Calculations similar to those for light projectiles show good agreement for Li^6 scattering from C^{12} and O^{16} at energies near 20 MeV. The vector analyzing powers are large even though the spin–orbit interaction makes a difference in energy between spin-up and spin-down states of only 0.1 MeV in grazing collisions of Li^6 with target nuclei, compared with a central potential of about 50 MeV. A polarized heavy-ion beam is a sensitive probe of interactions near the nuclear surface.

Tensor-polarized (aligned) Li^6 and Li^7 beams have dramatically different elastic-scattering differential cross sections at energies near the Coulomb barrier, as shown in figure 8, even though the cross sections for unpolarized beams are indistinguishable. The explanation is essentially the same as that given above for deuteron D-state effects in ($\vec{d}$,p) reactions, namely that scattering of highly deformed Li^7 (quadrupole moment Q = 40 mb) is very sensitive to spin alignment, whereas scattering of nearly spherical Li^6 (Q = 0.8 mb) is quite insensitive to alignment.

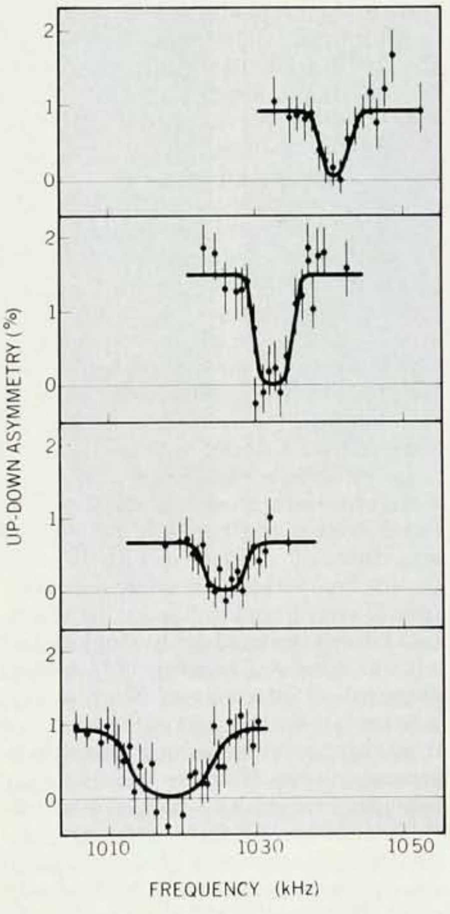
A group at the Osaka University has used the nmr technique described above to measure the polarization of B^{12} nuclei produced in the reaction Mo^{110} (N^{14}, $\vec{B}^{12}$) Ru^{102}. For such heavy nuclei, classical dynamics adequately describes the essentials of the interaction, including the polarization of the B^{12} transverse to the reaction plane.

It is expected that total reaction cross sections in polarized heavy-ion bombardment will depend on polarization state. For sodium-23 scattering from nickel-58, the difference in total reaction cross sections between transverse and longitudinal polarizations for energies near the Coulomb barrier is predicted to be about 20 percent. Fusion and fission of very heavy nuclei usually occur between non-spherical systems, so that a detailed understanding of reaction cross sections with polarized heavy nuclei may lead to better understanding of fission processes.

Techniques for producing more intense polarized beams and targets with a higher density of polarized nuclei are advancing rapidly. Fundamental tests of symmetries will thus become even more accurate than at present. Experiments previously performed only with unpolarized nuclei will use polarization to increase their sensitivity to spin-dependent effects. For example, the scattering of fast polarized neutrons is very poorly understood compared with proton scattering because polarized neutron production and detection are still relatively inefficient. As the differences between the available polarized and unpolarized beam intensities and target densities diminish, there will be increased interest in experiments with enhanced sensitivity to nuclear polarization.



Elastic scattering of Li^6 (black) and Li^7 (color) incident upon Ni^{58} nuclei. The lithium nuclei have energies of 14.5 MeV, an energy near the Coulomb barrier. We show (upper graph) the ratios of the cross sections for unpolarized beams to the Rutherford-scattering cross sections for point-charge nuclei, and (lower graph) the fractional changes in cross sections for aligned beams, both as functions of the lithium scattering angle. (From ref. 4) Figure 8



The β-asymmetry versus nmr frequency for Li^8 implanted in $LiIO_3$ is measured with the equipment shown in figure 1. There are four possible transitions between the $2J + 1$ substates for the spin-2 Li^8 nuclei. A single one of these is excited by driving the other transitions strongly enough with rf fields to equalize the magnetic substate populations. (From ref. 1). Figure 7

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Details of many of the topics reviewed here are in *Proceedings of the Fourth International Symposium on Polarization Phenomena in Nuclear Reactions* W. Grüebler, V. König, eds., Birkhäuser, Basel (1976), and in *High Energy Physics with Polarized Beams and Targets* (M. L. Marshak ed.) American Institute of Physics, New York 1976).

A bibliography of references that expand on many of the ideas in this review has been deposited with the Physics Auxiliary Publication Service at the AIP. Request the "Physics with Polarized Nuclei" bibliography, number PAPS PHTDA-32-32-11. Order by number and Journal reference; the price is $1.50 for each microfiche or $5 for a photocopy.

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