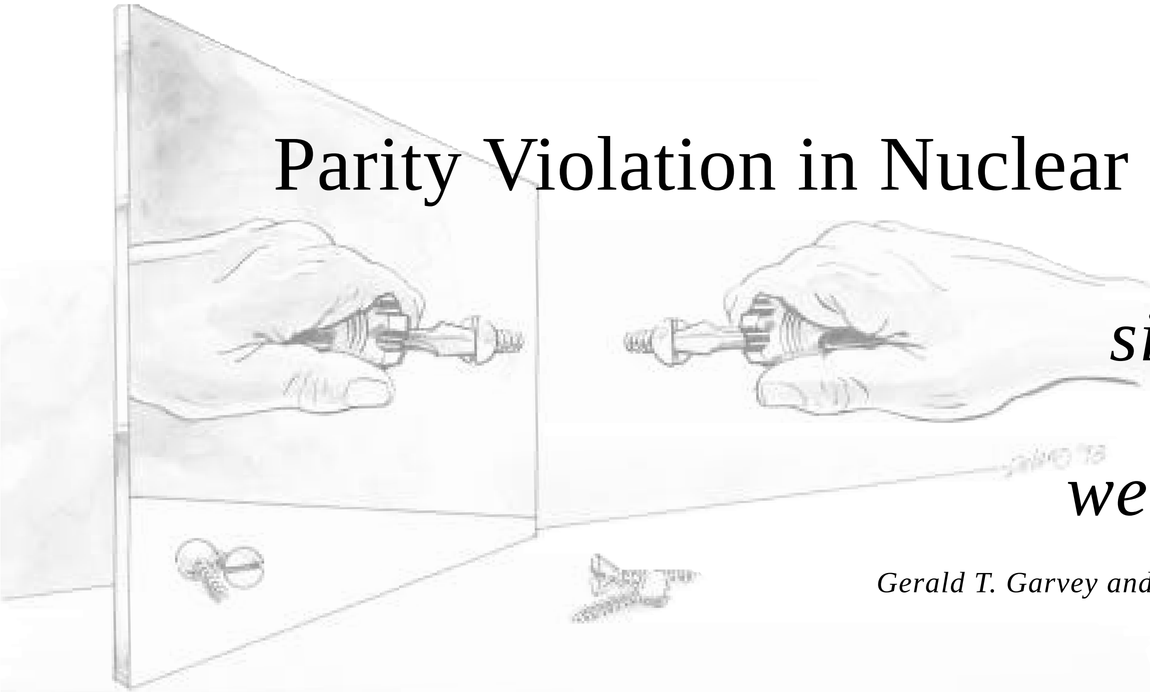
Parity Violation in Nuclear Physics



signature of the weak force

Gerald T. Garvey and Susan J. Seestrom

The elegant and concise description of the physical world contained in the standard model of electromagnetic, weak, and strong interactions (see “Unification of Nature’s Fundamental Forces”) is supported by a vast body of experimental data. Often only the first or the most precise experiments are cited as providing the requisite body of supporting data. However, the information and techniques developed by the world community of experimental particle and nuclear physicists has provided the broad base on which this powerful model has been constructed.

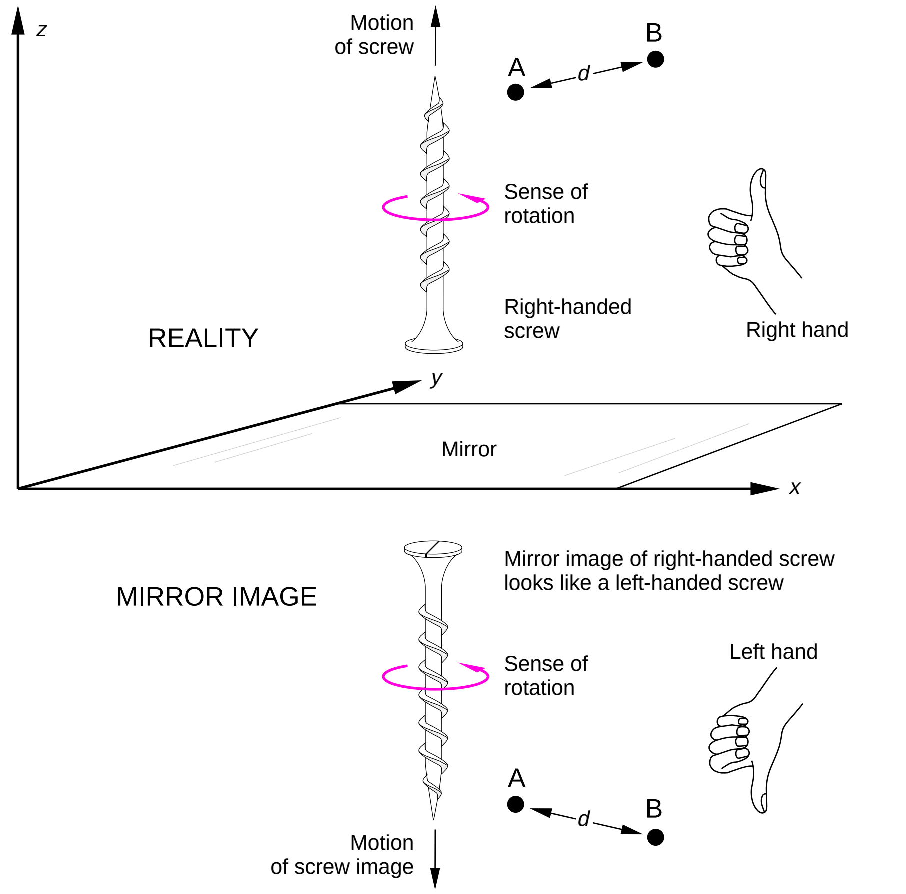
Los Alamos experimentalists, particularly in the Physics and Medium-Energy Physics Divisions, along with university users of the Los Alamos Meson Physics Facility (LAMPF), have played a role in building that base. Many of the major contributions by Laboratory scientists have been in the realm of neutrino physics. For example, they have established the most accurate upper limit on the mass of the electron antineutrino from very careful measurements of tritium beta decay. They also made the first measurements of the scattering of electron neutrinos from electrons, which showed that the interference between the charged and neutral currents of the weak interaction has a negative sign. This result has implications for the well-known solar-neutrino puzzle. The findings of Laboratory scientists support the standard model and have been among the most sensitive tests of its validity. However, since aspects of this research have been reported in previous editions of *Los Alamos Science*, it seems opportune to discuss another area of fundamental research in nuclear and particle physics at the Laboratory. This tale involves the measurement of the strength of the parity-violating interactions between strongly interacting particles—for example, between two neutrons or a neutron and a proton.

Before 1956 physicists believed that all the fundamental interactions in nature would be unchanged by a mirror reflection (or parity inversion). Imagine a basic interaction between two particles described in the orthogonal coordinate system (x, y, and z) as shown in Figure 1. A mirror reflection that inverts the z-axis (z goes to $-z$) results in the configuration shown in the mirror image. The familiar interactions, such as gravity and the interaction between electric charges, depend only on the distance d between the interacting particles, and so a description of those forces is completely unchanged by a parity transformation in which any one of the coordinate axes is inverted, such as in the mirror reflection shown in Figure 1. In the second type of parity transformation, all three axes are simultaneously inverted (x goes to $-x$, y goes to $-y$, and z goes to $-z$), and again the description of the familiar forces remains unchanged. Such interactions are said to be parity-conserving. For a long time physicists thought that all basic interactions must be parity-conserving. But if an interaction depends on the “screw”-like behavior of particles, its description will not be invariant under a parity transformation. Consider the screw in Figure 1; it has right-handed threads, so when it is rotated as shown, it advances in the $+z$ direction (up, in the figure). Its mirror image, however, has left-handed threads. Further, as the screw rotates, its mirror image rotates in the same direction but advances in the $-z$ direction.

Screws can be machined with either right-handed or left-handed threads, so their handedness (the relationship between the direction of rotation, or spin, and the direction of motion) is not an intrinsic property of nature. However, if an elementary particle with intrinsic spin has a fixed handedness (a fixed relationship between its spin direction and its direction of motion), the description of the particle will change under a parity transformation and it is said to violate parity conservation. Likewise if a basic interaction between particles involves only the left-handed or only the right-handed “screw”-like behavior of the particles, the interaction is said to violate parity conservation.

In 1957 it was demonstrated that the interaction responsible for the beta decay of a neutron into a proton, an electron, and a neutrino violates parity conservation. Specifically, when cobalt-60 nuclei, spinning in the same direction around the *z*-axis in the presence of a magnetic field in the +*z* direction, underwent beta decay, they emitted more electrons with a component of momentum in the –*z* direction than in the +*z* direction. This result is not invariant under a mirror reflection, indicating that the interaction responsible for the decay process, called the weak interaction, does not conserve parity. Further, the direction and amount of asymmetry indicated that the weak interaction is left-handed and violates parity in a maximal way. The reason that the weak interaction is left-handed is because the carriers of the weak force (the particles that are exchanged in weak processes), namely the W^+, W^-, and Z^0 bosons, interact with the left-handed component of particles and the right-handed component of antiparticles. (It is interesting to note that although the W^+, W^- , and Z^0 bosons were postulated much earlier to unify the description of the electromagnetic and weak interactions, they were first directly created and observed at the European Center for Nuclear Research (CERN) in 1982.)

Neutrinos and antineutrinos are particles that participate in, as far as we know, only weak interactions. Thus, it is not a surprise that these



$F_{\text{gravity}} \propto \frac{1}{d^2}$ and is therefore unaffected by mirror reflection.

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Figure 1. Effects of a Mirror Reflection
A mirror reflection is one type of parity transformation. In the figure the reflection inverts the *z* axis. The distance between points A and B is unchanged in the mirror image, so that the descriptions of the gravitational and electrostatic forces between, say, two electrons located at A and B would would also be unchanged. In contrast, the mirror image of the right-handed screw is a left-handed screw. When turned in the direction indicated by the red arrows, the screw advances in the +*z* direction whereas its mirror image advances in the °*z* direction. Note that if you curl the fingers of your right hand along the red arrow, your thumb points up, in the direction of motion of the right-handed screw. Alternatively, if you curl the fingers of your left hand along the red arrow, your thumb points down, in the direction of motion of the screw’s left-handed mirror image. Forces that depend on the relationship of spin rotation to direction of motion violate parity conservation.

massless particles with intrinsic spin show a fixed handedness. A neutrino always appears to spin clockwise when it is coming toward the observer and is therefore a left-handed particle, whereas the antineutrino appears to spin counterclockwise when it is coming toward the observer and is therefore a right-handed antiparticle.

The fact that the neutron decays via the weak interaction into a proton plus an electron and antineutrino means that the neutron and proton, which are known to interact through the strong force, must also interact through the weak force; otherwise they could not be involved in weak decay processes. One can therefore ask how the weak force affects the interaction between two nucleons (the neutron and the proton look the same to the strong force and are both called nucleons). The strong

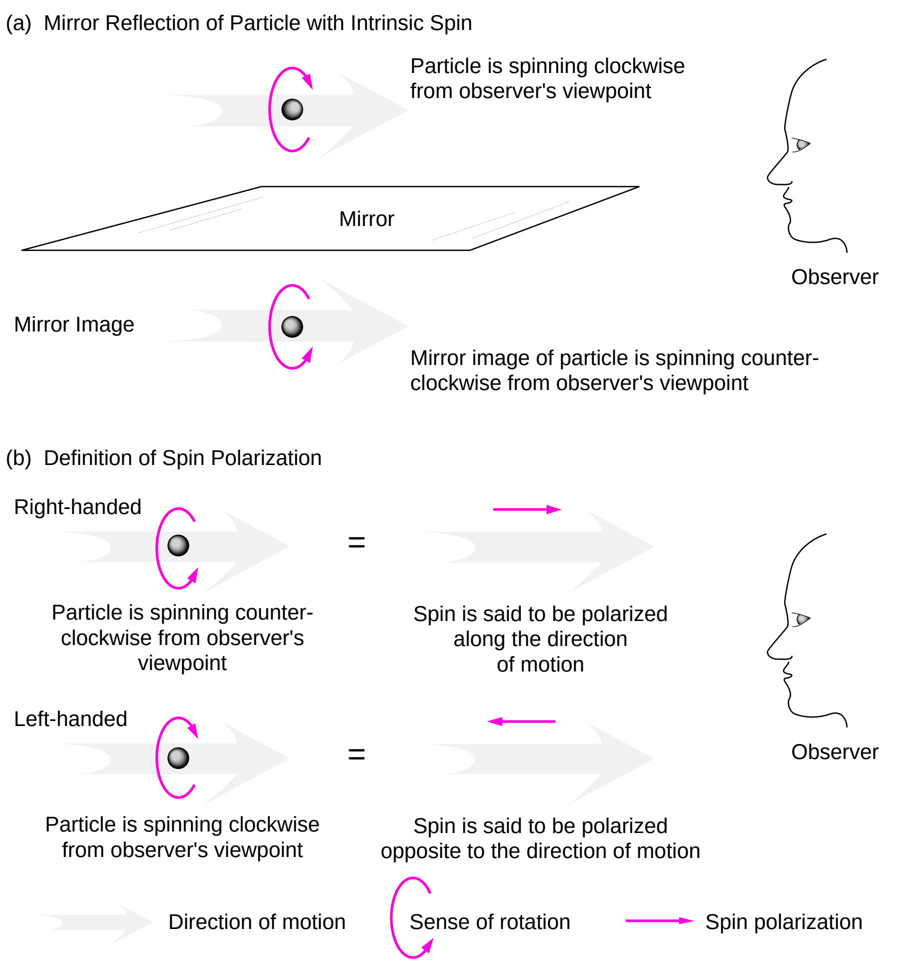


Figure 2. Mirror Reflection of a Particle with Intrinsic Spin
(a) A proton is moving toward the observer and is spinning around the direction of motion as indicated by the red arrow. The mirror image of the proton is also shown. To the observer, the proton spins clockwise, whereas the mirror image of the proton spins counterclockwise as both are moving toward the observer. Therefore if parity is conserved, the probability that a proton is scattered by a target should be independent of its spin direction, provided that the target nuclei are spinning in random directions. (b) The direction of spin is often represented by a vector that is along the axis of spin rotation. Here the axis of spin rotation of a proton is parallel to its direction of motion. According to convention, when the relation between the rotation and the motion is like that of a right-handed screw, the spin vector points in the same direction as the direction of motion and the proton is said to have its spin polarized along the direction of motion. When the relation between the rotation and the motion is like that of a left-handed screw, the spin vector points opposite to the direction of motion and the proton is said to have its spin polarized opposite to the direction of motion.

force dominates the interaction between two nucleons; specifically, the ratio of the strength of the weak interaction to that of the strong interaction is about 1 to 10 million. Typically the effects of such a small interaction would be next to impossible to detect, but the weak interaction has a unique signature in that it is the only interaction in the standard model that violates parity. Hence measurement of the amount of parity violation in a given process is a direct measure of the role played by the weak interaction in that process.

As was mentioned earlier, parity violation was discovered in 1957, but it was not until seven years later that the first clear parity-violating effect was measured in processes other than weak decays of nuclei. In 1964 a group headed by Yuri G. Abov in the then Soviet Union observed parity violation in the capture of polarized neutrons by the nucleus cadmium-113. The gamma rays emitted following the neutron capture were emitted preferentially in the direction of the neutron polarization, which indicated that parity was violated. Thus the weak interaction between the nucleons within the nucleus was producing measurable effects. Unfortunately the complexity of the relative motions of the nucleons in the cadmium nucleus made it impossible to determine the strength of the weak interaction between pairs of nucleons from that experiment.

In 1970 a Los Alamos group led by Hans Frauenfelder, Dick Mishke, and Darrah Nagle began investigating parity violation in the scattering of protons from protons. For their first experiments they used the polarized ion source installed by Joe McKibben in the tandem Van de Graaff accelerator. The polarized ion source and its subsequent versions were essential to the experiment because they produce a beam of protons all of which are spinning in the same direction.

The proton has intrinsic spin but no intrinsic handedness, so its spin direction can be changed relative to its direction of motion. Figure 2 illustrates that the ability to manipulate the proton's spin direction in a known and controlled way is valuable in investigating the degree of parity violation in scattering two protons from one another. Figure 2a depicts a fast-moving proton such as would be found in a proton beam from an accelerator, as well as its mirror image. The proton is moving to the right and appears to be spinning clockwise to the observer at right. (It is behaving like a left-handed screw.) In the mirror image the proton is again moving to the right but appears to be spinning counterclockwise to the observer. (It is behaving like a right-handed screw.) Thus, if the principle of parity conservation applies, protons rotating clockwise or counterclockwise relative to their direction of motion (or, as defined in Figure 2b, with their spins polarized either along or opposite the direction of motion) should be scattered identically from a target composed of protons that are spinning in random directions.

A container of hydrogen provides a suitable target because the average spin of the protons (hydrogen nuclei) in the target is zero. In the Van de Graaff experiment protons polarized along the direction of motion were scattered from the target, and then protons polarized in the opposite direction were scattered. The total scattering cross section, or probability of scattering,

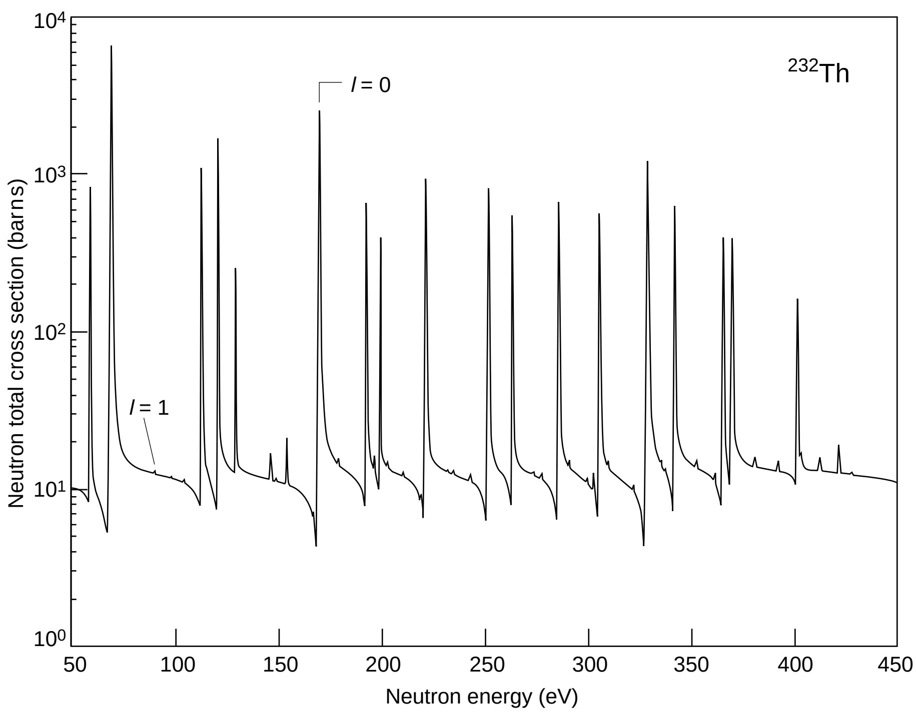
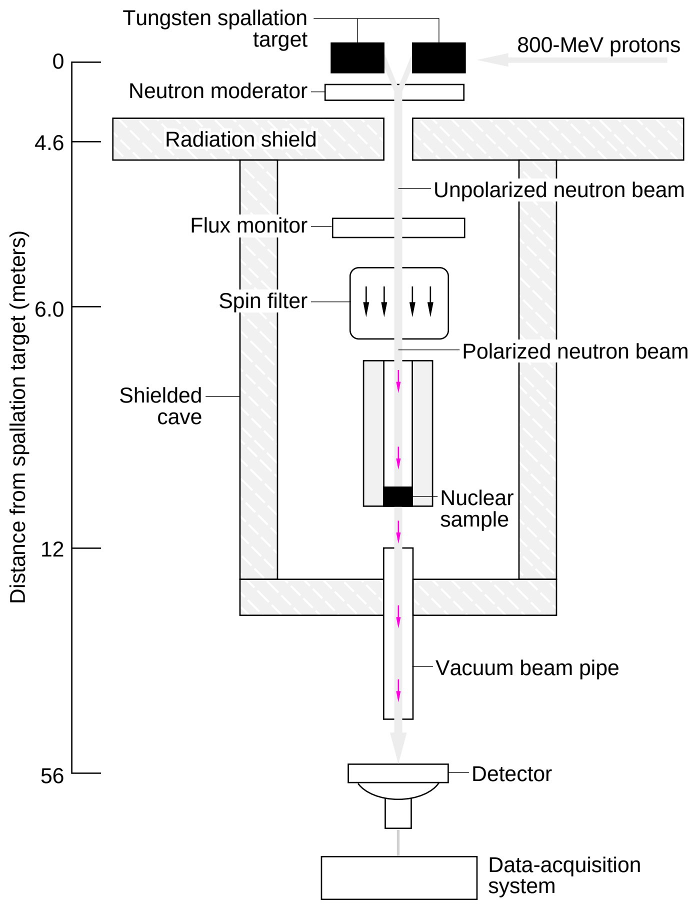


Figure 3. Total Cross Section for Scattering and Absorption of Neutrons by ^{232}Th

The total cross section (or probability) for the interaction of neutrons with ^{232}Th is plotted as a function of neutron energy. The many sharp peaks in the cross section are called resonances and occur when the neutron energy equals the energy of an excited state of the compound nucleus ^{233}Th and can therefore be absorbed by ^{232}Th. The tall peaks occur at energies of nuclear states with orbital angular momentum equal to zero ($l = 0$) and the small peaks (lower by two orders of magnitude) occur at energies of nuclear states with $l = 1$. Both types of resonances can be studied with great sensitivity for the parity-violation effects, which are expected for $l = 1$ but not for $l = 0$ resonances.

was measured in each case. The Van de Graaff experiment began in the early seventies and was not concluded until the end of the decade. It was the first scattering experiment anywhere in the world in which parity violation was observed. Protons with spins polarized along their direction of motion were scattered slightly more often than those with opposite polarization. The reason the experiment took so long to carry out was that the measured asymmetry between the two neutron polarizations was very small. The protons scatter mainly as a result of strong interactions, so the difference (resulting from the weak interactions) between the fraction of particles scattered for two different spin polarizations was only 2 parts in 100 million. Thus a variety of new techniques had to be invented to make the measurement possible. After the Van de Graaff experiment was completed, the research group carried out a further measurement of parity violation using a much-higher-energy polarized proton beam available at LAMPF. The observed effects

Figure 4. Setup for Parity-Violation Experiment at LANSCE
Neutrons are produced by interaction of 800-MeV protons with a split tungsten target shown at the top of the figure. The energies of the neutrons so produced range from almost zero to nearly 800 MeV. The neutrons pass first through a moderator that reduces the energy of the neutrons to the eV or keV range. Because the neutrons are produced in pulses and because the time required to produce and moderate the neutrons is small compared to their time of flight to a detector 56 meters away, the energy of each detected neutron can be measured from its measured time of flight. The beam of moderated neutrons passes through a spin filter—a material in which the proton spins have been aligned in the same direction as the direction of motion of the neutrons (large red arrows). Those neutrons whose spin directions are opposite that of the protons in the spin filter are absorbed or scattered out of the beam. The neutrons with the same spin direction as the protons interact more weakly with the protons and remain in the beam. The neutron beam emerging from the spin filter contains neutrons with only one spin direction (small red arrows) rather than both and is thus polarized. As the polarized neutron beam passes through the sample, its intensity is reduced as neutrons are absorbed by or scattered from the nuclei in the sample. A detector measures the number and the times of arrival of the neutrons that are transmitted through the sample. The polarization of the neutron beam can be reversed (by reversing the polarization of the protons in the spin filter) and the experiment repeated. If the measured fraction of neutrons transmitted through the sample at a given resonance energy is different for one neutron polarization than for the other, then that resonance exhibits parity violation.



were only somewhat larger, at the level of a few parts in 10 million, which is near the expected value at that energy. However, because the parity-violating effect was so small, experimental errors were about the same size as the effect and so the precise strength of the weak force between two nucleons could not be determined.

In the meantime research groups in the Soviet Union were reporting parity-violating effects one million times larger in the absorption of very-low-energy polarized neutrons by certain heavy nuclei. Neutrons carry the same amount of intrinsic spin as protons do and, like the proton, their spins can be polarized along or opposite to the direction of motion (see Figure 2). The cross sections differed depending on the polarization of the incident neutrons, indicating parity violation. It was again, however, impossible to deduce the strength of the weak interaction between two nucleons from the observed degree of parity violation in these experiments because even though the effect of the weak force was amplified many times by nuclear motions, the amount of amplification could not be quantified.

Figure 3 shows the measured probability of a low-energy neutron interacting with a thorium-232 nucleus as a function of energy of the incident neutron. The series of large bumps evident in the data appear at the energies of quantum states of the compound thorium-233 nucleus. When the energy of the incident neutron corresponds to the energy of one of these states, the neutron is said to be at a resonance and the incident neutron can readily share its energy with the neutrons and protons in the thorium target nuclei. In other words, at a resonance there is a large probability for the neutron to be absorbed into a thorium nucleus. At other energies the neutron is much less likely to interact, and when it does interact, it is simply deflected from the ^{232}Th nucleus without sharing its energy. If the probability of absorption at a resonance depends on the spin polarization of the incident neutron, then the resonance process exhibits parity violation.

The members of the Triple Collaboration* realized that if parity violation could be measured at several resonances of the same nucleus, one could determine an average value of the magnitude of the parity violation that would be independent of the statistical properties of the nuclear motions and therefore could be used to estimate the strength of the underlying nucleon-nucleon weak interaction. As indicated above, the effect of parity violation on nucleon-nucleon interactions is very small. However, the effect is amplified by a factor of about 1 million by the motion of many nucleons in the nucleus to yield the large parity violations observed for the scattering of a neutron by a nucleus at a resonance. The size of the amplification depends on statistical properties of the quantum states of the nucleus and therefore the amplification has a random distribution. By averaging the parity-violating effects observed at many resonances, the average value of the amplification can be determined. Our theoretical models of the nucleus are sufficiently detailed to deduce from the observed average amplification in a nucleus containing many nucleons a fairly good estimate of the strength of the weak interaction between two nucleons.

The Triple Collaboration also realized that the Los Alamos Neutron Scattering Center (LANSCE) was an ideal facility at which to carry out the necessary measurements. One of the principal advantages of the LANSCE neutron source over reactor neutron sources is that the range of available neutron energies is much greater. A typical reactor neutron source has a very limited flux of neutrons with energies above 10 eV, whereas Figure 3 shows that measuring the parity violation at a number of resonances of ^{232}Th requires the availability of neutrons at energies ranging up to several hundred eV.

Since the features of the LANSCE facility are essential to the successful experimental program undertaken by the Triple Collaboration, we describe it briefly. The major elements of the facility are LAMPF, which provides 500- to 700-microsecond-long trains

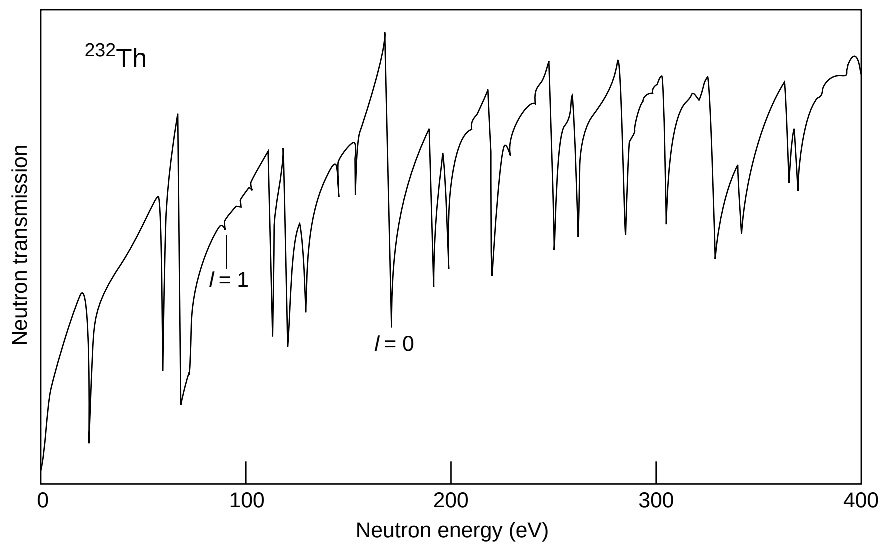


Figure 5. Neutron Transmission Spectrum of ^{232}Th
Shown here are the measured values for the fraction of neutrons transmitted through a ^{232}Th sample as a function of neutron energy. The fraction of neutrons transmitted decreases sharply when the neutron energy is at a resonance of ^{232}Th. That is, the neutrons can be absorbed by ^{232}Th to form an excited state of the compound nucleus ^{233}Th. The large dips are at the energies of the l = 0 states of the compound nucleus ^{233}Th; these resonances do not exhibit parity violation. Smaller dips, such as the three between 80 and 110 eV, are at the energies of the l = 1 states of the compound nucleus ^{233}Th, which can exhibit parity violation and are therefore of interest in these experiments.

*The Triple Collaboration is a collaboration between Los Alamos National Laboratory, North Carolina State University, Duke University, Triangle Universities Nuclear Laboratory, TRIUMF (Canada), University of Technology at Delft (The Netherlands), KEK (Japan), and the Joint Institute for Nuclear Research (Russia). The collaboration was formed to study fundamental symmetries using polarized neutrons at LANSCE.

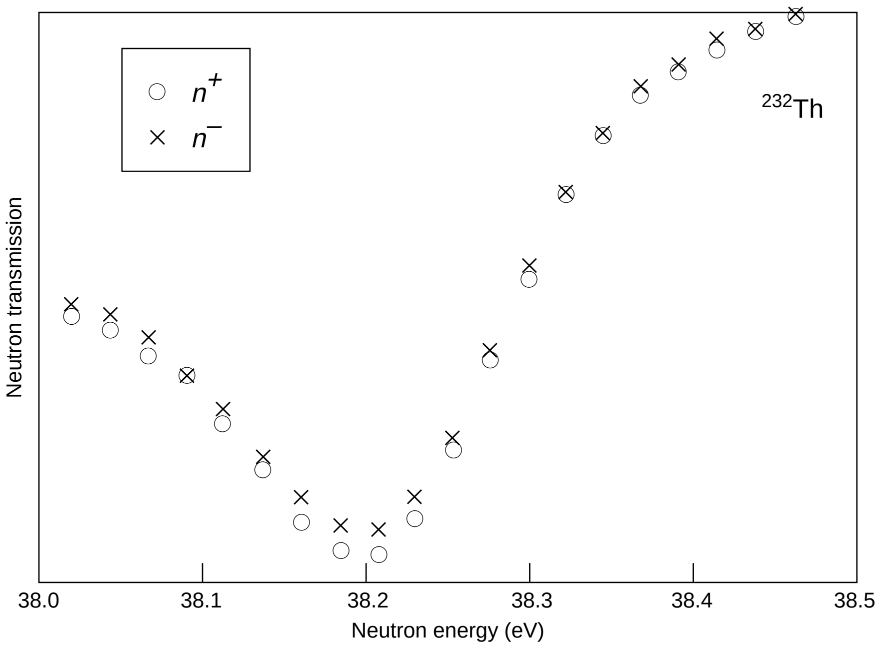


Figure 6. Parity Violation in a Neutron Resonance of ^{232}Th
Transmission data for two different neutron polarizations are shown near the l = 1, $J = \frac{1}{2}^-$ resonance of ^{232}Th at 38.2 eV. Results for neutrons polarized along the direction of motion (n^+) are designated by circles. Results for neutrons of the opposite polarization (n^-) are designated by crosses. The circles and crosses are close together over most of the energy range shown. At the resonance (the dip in the transmission spectrum) the circles clearly fall below the crosses; that is, more neutrons polarized along the direction of motion are absorbed by ^{232}Th than neutrons polarized opposite to the direction of motion. Thus this resonance exhibits parity violation.

of 250-nanosecond pulses of 800-MeV H^- ions; the Proton Storage Ring, which combines the many short H^- pulses in each train into a single, intense 250-nanosecond proton pulse; and finally the LANSCE spallation source, in which the incredibly intense pulse of protons is converted to neutrons through the process of spallation. That is, when the 800-MeV protons impact the tungsten target, each proton liberates about 20 neutrons from the neutron-rich tungsten nuclei. As a result each intense pulse from the storage ring creates about 10^{13} neutrons all within a quarter of a microsecond. This time is very short compared to the time it takes the neutrons to travel to a detector some 50 meters away from the area where they are produced. Therefore the measurement of a neutron's time of flight over the known distance from source to detector gives a direct measurement of the neutron's speed and hence its energy. Thus LANSCE not only generates large numbers of neutrons over the necessary range of energies but also produces neutrons whose energies can be accurately measured. Only one requirement for studying parity violation is missing: the neutrons coming from the spallation source do not have a definite polarization, or spin direction.

Figure 4 shows a schematic setup of the experiment and indicates how a beam of polarized neutrons is produced. The neutrons produced in the tungsten target are not polarized; that is, the spin of each has an equal probability of pointing along or opposite its direction of motion. They are passed through a spin filter, a special material in which the protons in water (or hydrocarbon) molecules are polarized along the direction of motion of the incoming neutron beam. The neutrons with spins polarized opposite to those of the protons in the spin filter interact most strongly with those protons and are therefore scattered out of the beam. Thus the neutrons that pass through the spin filter are those with spins polarized along the direction of motion. In this way a polarized neutron beam is produced. By changing the direction of proton polarization in the spin filter, neutrons can be polarized either along or opposite their direction of motion.

A beam of neutrons polarized in one direction is passed through a particular nuclear sample (for example, ^{232}Th), and the experimenters measure the fraction that are transmitted through the sample. The experiment is repeated with neutrons polarized in the opposite direction. If parity is conserved, the fraction transmitted through the target sample would be the same for both experiments. Figure 5 shows neutron transmission through a ^{232}Th sample as a function of energy. The neutron transmission is reduced when the neutrons have the same energy as a resonance because then the probability of neutron absorption by the nuclei is greatest. Figures 6 and 7 show examples of the data obtained for the transmission of neutrons with opposite polarizations through a ^{232}Th target and a ^{238}U target, respectively. Figure 6 shows the transmission for the two neutron polarizations for a $J = \frac{1}{2}^{-}$, l = 1 resonance of ^{232}Th at 38.2 eV, where J is the total angular momentum of the resonance, l is the orbital angular momentum, and the minus sign denotes the parity of the resonance. (The parity of a resonance can be + or –, depending on whether the wave function of the resonance remains unchanged or reverses sign under a parity inversion. Because the sign of the wave function is unmeasurable, negative-parity wave functions do not violate parity conservation.) The top graph in Figure 7 is a plot of the asymmetry parameter ε as a function of neutron energy for transmission through ^{238}U. The asymmetry ε is a measure of the difference in transmission for the two neutron polarizations and makes small differences easier to detect. The the figure shows a small asymmetry for the $J = \frac{1}{2}^{-}$, l = 1 resonance of ^{238}U at 64 eV and no asymmetry at the large $J = \frac{1}{2}^{+}$, l = 0 resonance at 66 eV. This dependence of neutron transmission on the total angular momentum of the resonance and its parity is a well-understood feature of the *strong* force, but beyond the scope of this article to explain.

The first experiment by the Triple Collaboration was performed on uranium-238. Seventeen resonances were examined and five showed measurable asymmetries indicating parity violation. The experiment on ^{238}U was the first in which a research team had seen parity violation in more than one resonance of a single nucleus. A later experiment on the isotope ^{232}Th (whose resonances are depicted in Figures 3, 5, and 6) studied twenty-three resonances of which seven had measurable asymmetries ranging between 1 and 10 percent. This data sample is sufficiently large that a value can be extracted for the average strength of the weak interaction between a single nucleon and all the nucleons in the ^{232}Th nucleus. This result is serving to refine our knowledge of the weak interaction between two nucleons and should prove far more useful as experimental techniques are improved and additional data are taken. The weak interaction between nucleons will eventually be understood in terms of

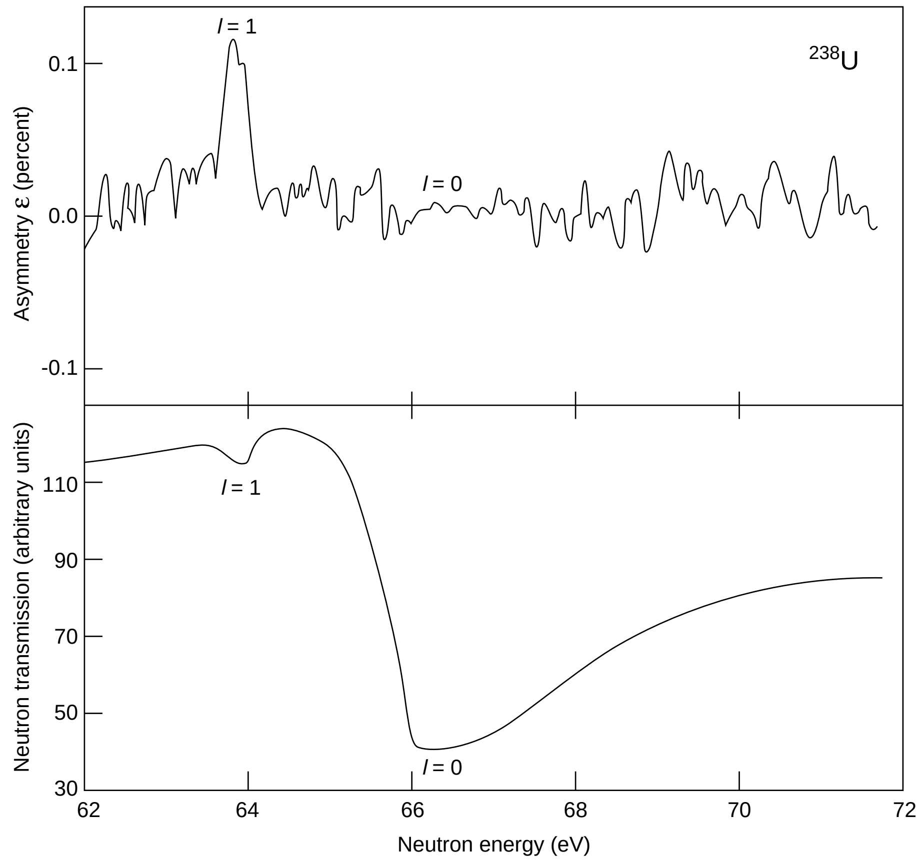


Figure 7. Parity Violation in a Neutron Resonance of ^{238}U
The parity-violating effect at the 64-eV, l = 1 resonance of ^{238}U is smaller than that shown in Figure 6 and is more easily detected by plotting the results for the two neutron polarizations in terms of the asymmetry parameter $\varepsilon \equiv (T^+ - T^-)/(T^+ + T^-)$, where T^+ is the transmission for neutrons polarized along the direction of motion and T^- is the transmission for neutrons polarized opposite to the direction of motion. The asymmetry parameter ε plotted in the top graph has statistical fluctuations over the energy range shown except at the 64-eV resonance where the asymmetry between the two neutron polarizations is 0.1 percent. The sum of the transmissions for both polarizations ($T^+ + T^-$) is shown in the bottom graph. The parity-violating resonance at l = 1 appears as a small dip in transmission at 64 eV, whereas an l = 0 resonance at 66 eV appears as a large dip in transmission. As expected the plot of the asymmetry parameter ε shows no asymmetry at the energy of the l = 0 resonance.

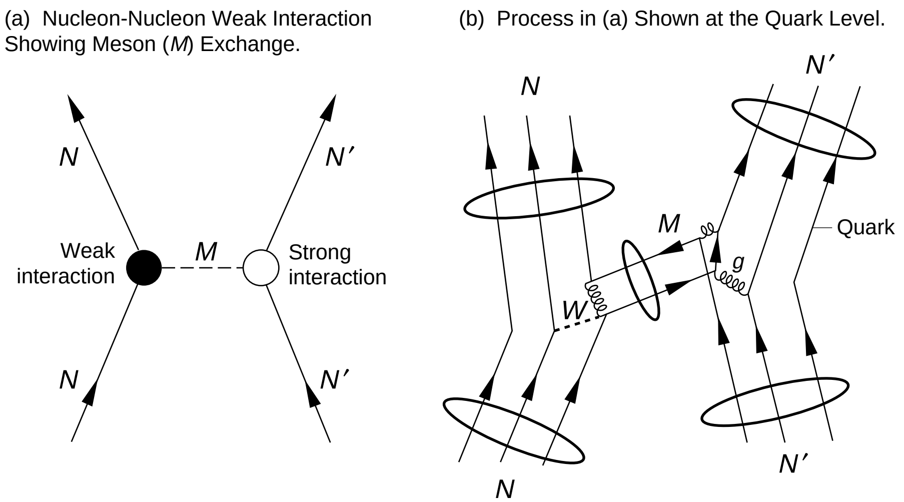


Figure 8. The Nucleon-Nucleon Weak Interaction at the Quark Level
(a) The weak interaction between nucleons N and N' is often described as an exchange of the meson M, in which the open circle is a strong interaction meson-nucleon vertex, and the solid circle is a weak interaction meson-nucleon vertex. (b) This cartoon of the weak interaction between nucleons N and N' shows the possible interactions that might take place involving the three quarks composing each nucleon and the quark-antiquark pair composing the meson. The dotted line is a W boson, which carries the weak force. The spiral lines are gluons, the carriers of the strong force.

interactions among the quarks composing the nucleons and the carriers of the weak force (Figure 8).

One feature of the observed results is difficult to understand. There seems to be a mysterious preference for a positive sign to the asymmetry. That is, neutrons with spins polarized along the direction of motion tend to be scattered more readily than neutrons with opposite polarization. In fact, in the case of ^{232}Th, all seven observed asymmetries showed this preference. Several papers dealing with this issue have been published, but as yet no satisfactory explanation has emerged.

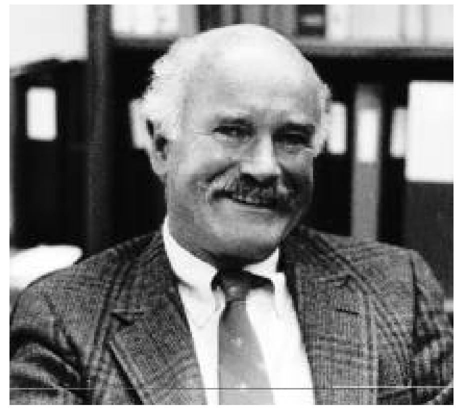
It is clear that the facilities and personnel at Los Alamos in conjunction with the world scientific community continue to contribute to the store of scientific knowledge that will represent one of the great legacies of the last half of this century. ■

Further Reading

C. M. Frankle, J. D. Bowman, J. E. Bush, P. P. J. Delheij, C. R. Gould, D. G. Haase, J. N. Knudson, G. E. Mitchell, S. Penttilä, H. Postma, N. R. Roberson, S. J. Seestrom, J. J. Szymanski, S. H. Yoo, V. W. Yuan, and X. Zhu. 1992. Parity nonconservation for neutron resonances in ^{232}Th. *Physical Review C* 46: 778.

J. D. Bowman, C. D. Bowman, J. E. Bush, P. P. J. Delheij, C. M. Frankle, C. R. Gould, D. G. Haase, J. Knudson, G. E. Mitchell, S. Penttilä, H. Postma, N. R. Roberson, S. J. Seestrom, J. J. Szymanski, V. W. Yuan, and X. Zhu. 1990. Parity nonconservation for neutron resonances in ^{238}U. *Physical Review Letters* 65: 1192.

V. W. Yuan, C. D. Bowman, J. D. Bowman, J. E. Bush, P. P. J. Delheij, C. M. Frankle, C. R. Gould, D. G. Haase, J. Knudson, G. E. Mitchell, S. Penttilä, H. Postma, N. R. Roberson, S. J. Seestrom, J. J. Szymanski, and X. Zhu. 1991. Parity nonconservation in polarized-neutron transmission through ^{139}La. *Physical Review C* 44: 2187.



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