Parity-Violating Nuclear Forces

The overthrow of parity conservation during the late 1950's is one of the most significant landmarks in physics history. C. N. Yang and T. D. Lee postulated nonconservation of parity (reflection symmetry) in weak interactions as a result of their theoretical studies of K-meson decays. Several experimental physicists immediately grasped the significance of the Yang-Lee hypothesis, and within a few months three different experiments indicated that parity is indeed violated in weak interactions. The first and most famous experiment is that of C. S. Wu and her collaborators who studied beta decay of cobalt-60. Wu and her colleagues published their results only days before the two other groups who observed parity violation in μ-meson decays.

The parity-violating theory of weak interactions was extended, in 1958, by Richard Feynman and Murray Gell-Mann to include additional sources of parity violation (*1*). In particular, their theory allowed nucleons (protons and neutrons) to interact via a small parity-violating weak force. As a consequence of such interaction, nuclear energy levels previously believed to be pure parity states would be expected to contain a small admixture of the opposite parity. Owing to the small size of the weak force in comparison with that of the customary parity-conserving strong force between nucleons, experimental confirmation did not come as quickly as it did for the postulation of Yang and Lee. The first experimental observation of parity violation in nuclear forces was reported in 1964, but when this experiment was repeated elsewhere no effect was observed. There was general disagreement between various experimental results until late 1969, when an experiment at the California Institute of Technology confirmed an earlier Russian result. At long last, parity violation of nuclear forces had been demonstrated.

Feynman and Gell-Mann modeled their theory of weak interactions—dubbed the "universal theory of weak interactions"—after electromagnetic theory. Inasmuch as electromagnetic processes can be understood as the interaction of two currents, they reasoned that weak nuclear phenomena could also proceed by way of a current-current interaction. Nuclear beta decay can be described as the interaction of a nucleon (proton and neutron) current with a lepton (electron and neutrino) current. The interaction of the lepton current with a strange-particle current allows for leptonic decays of strange particles, and so on. The "universal theory" also provided for the interaction of a current with itself, and the case of the interaction of a nucleon current with a nucleon current gives rise to parity violations in nuclear forces.

Two different schemes have been used to demonstrate parity violation in nuclear forces. Figure 1 shows the reaction used by Yu. G. Abov at the Institute of Theoretical and Experimental Physics, Moscow. Thermal neutrons with their spins aligned predominately in one spatial direction (polarized neutrons) are captured by a target of cadmium-113. The resulting nucleus, cadmium-114, is in an excited state and subsequently emits a gamma photon. If the photons have a preferred direction of emission, either parallel or antiparallel to the spins of the neutrons, parity is violated. In Fig. 1 the photon is emitted in a direction opposite to the spin vector of the neutron (antiparallel). The mirror image shows the photon traveling parallel to the spin vector since spin (angular momentum) is not inverted by the parity operation (spatial reflection). (Those readers who are familiar with vector analysis will recognize that spin is an axial vector.) Thus, if the gamma photons do not have an isotropic spatial distribution, the nuclear reaction and its mirror image are not identical. This situation constitutes parity violation.

Observing parity violation in nuclear forces is not an easy matter because the weak interactions between nucleons are smothered by the parity-conserving strong forces. C. S. Wu had such immediate success with her ^{60}Co experiment because the parity-violating weak force is dominant in beta decay. However, the strong forces between nucleons are about seven orders of magnitude greater than their weak forces. Looking for parity violation in nuclear forces, therefore, is like trying to hear a pin drop at a pop music concert. In order to observe such a small effect, about 10^{15} individual nuclear events must be recorded. Since the standard equipment of 10 years ago could cope with a maximum of 10^5 counts per second, only Methuselah could have performed such an experiment. (One year is equivalent to about 3×10^7 seconds.) Success could not be guaranteed unless either special nuclei that favored parity violation were found or new counting techniques were developed.

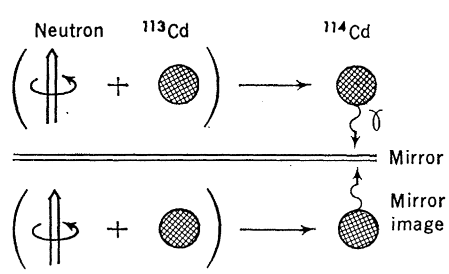

Fig. 1. Polarized thermal neutrons (the double arrow indicates the spin direction) are captured by ^{113}Cd. If the gamma photons from ^{114}Cd are emitted preferentially in one spatial direction, parity is violated.

Polarization of Thermal Neutrons

The first experimental evidence of parity-violating nuclear forces was reported by Yu. G. Abov, P. A. Kruptchitsky, and Yu. A. Oratovsky from Moscow (*2*). They polarized the thermal neutrons by scattering from cobalt magnets. The polarized neutrons then collided with the ^{113}Cd target. Cadmium-113 was selected as the target because the nuclear level of interest in the reaction product, ^{114}Cd, is close to other levels of the same angular momentum, but of opposite parity. This type of energy-level arrangement enhances the possibilities for observing parity violation. Abov and his co-workers detected an asymmetrical spatial distribution of photons emitted by ^{114}Cd. The asymmetry value of $-(3.7 \pm 0.9) \times 10^{-4}$ was correlated with the neutron spin as expected.

Elizabeth Warming did an experiment similar to Abov's at Risø, Denmark, in 1967. Since her results were not identical with Abov's, both improved and repeated their experiments. Now things are worse. Abov's newest result for the asymmetry, $-(3.5 \pm 1.2) \times 10^{-4}$, agrees with his first value (*3*). However, the newest Danish experiment, which Warming claims is the most reliable of all, shows no asymmetry. Her result is $-(0.6 \pm 1.8) \times 10^{-4}$ (*4*). Additional experiments of this type are being planned with the hope of sorting out these discrepancies.

The only noncontroversial evidence now for parity violation in nuclear forces comes from another method—

measurements of circularly polarized gamma photons emitted from unpolarized nuclei. In spite of the present agreement, the history of experiments by this method is not lacking in discrepancies. The basic idea of these experiments is quite simple. Photons spinning clockwise when approaching an observer would be seen as rotating counterclockwise by the observer on the other side of the mirror. As the nuclei are unpolarized and do not characterize a direction in space, the mere existence of polarized gamma photons violates parity (Fig. 2).

Since gamma photons are more energetic than those corresponding to visible light, ordinary polaroids are ineffective for analyzing the polarization of the gamma particles. Magnetized iron polarimeters are used instead. The scattering cross section for polarized gamma photons on the magnetized iron depends on the direction of magnetization. In the usual setup, the photons are emitted from the radioactive source and then scattered off the iron polarimeter into a detector fixed in space. If the photons are polarized, the counting rate will change when the polarimeter's magnetic field is reversed.

The Special Nucleus

As in the ^{114}Cd experiment, a special nucleus had to be found where the parity-conserving transition is inhibited, giving the parity-violating effects a chance to compete. One decay scheme that fits the bill is ^{181}Hf $(\beta+)$ ^{181}Ta* (γ) ^{181}Ta. The polarization of gamma photons emitted from tantalum-181 following the beta decay of hafnium-181 has been extensively studied over the past 6 years. In 1965, F. Boehm and E. Kankeleit of Caltech reported a circular polarization for the 482 kev gammas of $-(2.0 \pm 0.4) \times 10^{-4}$ using conventional pulse-counting techniques (*5*). However, this result was questioned 2 years later when V. M. Lobashov and his colleagues at the Yoffe Physico-Technical Institute, Leningrad, published new data. They designed and used a new, more sensitive technique to study the same decay and found a polarization of $-(6 \pm 1) \times 10^{-6}$ (*6*). The Russian value was ten times lower than the quoted uncertainty on the American value. Obviously, something had to give.

At the end of last November, Boehm in collaboration with J. C. Vanderleeden published new results for the ^{181}Ta decay, using a variation on Lobashov's technique. Their value (*7*) of $-(3.8 \pm 1.3) \times 10^{-6}$ now agrees with that of Lobashov (*6*). During the interim between Boehm's first and latest experiments at least seven other experiments on ^{181}Ta were performed in various countries including England and Germany. But last November marked the first time that two different experiments showed a definite parity-violating effect of the same magnitude.

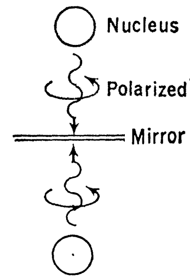

Fig. 2. The emission of polarized gamma photons from unpolarized nuclei violated parity conservation since the polarization of the gamma particles changes from left- to right-circular upon reflection.

In addition to that in ^{181}Ta, Lobashov and his co-workers (*8*) have discovered parity-violating effects for gamma transitions in lutetium-175 and potassium-41. Boehm and Vanderleeden corroborated their ^{175}Lu result. Only a short time ago B. Jenschke and P. Bock, Universität Karlsruhe, Germany, reported yet another example—this time in ^{180}Hf (*9*). That all of the successful experimenters used variations on Lobashov's original technique is well worth discussing.

Counting

In order to avoid the extraordinarily long time needed to count sufficient numbers of individual pulses, Lobashov used a detection system that integrated the electrical current caused by gamma particles arriving at his detector. This arrangement allowed him to use very intense radioactive sources that would jam equipment suitable for counting individual pulses. In the ^{181}Ta experiment he used about 500 curies of ^{181}Hf. The detector current due to the gamma photons was integrated over equal times (an allowance for decay of the source intensity was made) for both magnetic states in the iron polarimeter. Any difference between the integrated currents recorded for each magnetic setting was primarily attributed to circular polarization of the gamma particles. To improve the sensitivity of his apparatus, Lobashov coupled his integrating detector output to an astronomical pendulum accurately tuned to the frequency of magnetic reversals in the polarimeter. The pendulum resonated when the gamma particles were polarized. From the pendulum's resonant amplitude and phase, Lobashov could determine the magnitude of the polarization and its sign—that is, whether the polarization is right- or left-circular.

The main source of interfering background came from bremsstrahlung (the electromagnetic radiation produced by the sudden retardation of an electrical particle in an intense electric field) emitted in the beta decay of ^{181}Hf. Bremsstrahlung is composed of gamma photons that are produced when the beta particles are decelerated in the material surrounding the radioactive source. Since parity is violated in beta decay, the beta particles are polarized; as a consequence, the bremsstrahlung is also polarized. Control experiments are necessary to separate the amount of gamma circular polarization due to parity-violating nuclear forces from that due to circularly polarized bremsstrahlung.

We can expect that new experiments in this field will be mainly on the light nuclei. One prime prospect, the study of the spatial asymmetry of gammas emitted when polarized thermal neutrons are captured by deuterons, is currently being pursued in the United States and in Russia. The reason for this interest in the lower end of the periodic table is that nuclear theorists can do a better job of calculating the magnitude of the parity-violating effect in the lighter-weight isotopes than in the heavier ones. At present no accurate and comprehensive nuclear calculations exist which account for the experimental results discussed here. There have been several calculations, but in view of the complexity of the nuclei involved, many simplifying assumptions were introduced (*10*). In spite of these difficulties, the general agreement between theory and experiment indicates that the current-current formalism of the "universal theory of weak interactions" is a valid description of weak nuclear forces.

—GERALD L. WICK

References

1. R. P. Feynman and M. Gell-Mann, *Phys. Rev.* **109**, 193 (1958).
2. Yu. G. Abov, P. A. Kruptchitsky, Yu. A. Oratovsky, *Phys. Lett.* **12**, 25 (1964).
3. Yu. G. Abov *et al.*, *ibid.* **27B**, 16 (1968).
4. E. Warming, *ibid.* **29B** 564 (1969).
5. F. Boehm and E. Kankeleit, *Phys. Rev. Lett.* **14**, 312 (1965).
6. V. M. Lobashov *et al., Phys. Lett.* **25B** 104 (1967).
7. J. C. Vanderleeden and F. Boehm, *ibid.* **30B**, 467 (1969).
8. V. M. Lobashov *et al., ibid.* **30B**, 39 (1969).
9. B. Jenschke and P. Bock, *ibid.* **31B**, 65 (1970).
10. For a review, see E. M. Henley, *Annu. Rev. Nucl. Sci.* **19**, 367 (1969).