Conservation of Parity in Strong Interactions*

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An investigation was made of the angular distribution of the gamma rays produced by the capture of slow polarized neutrons in cadmium, indium, and silver. The portion of the intensity of the transitions from the spin-one capture state of Cd^{114} to the spin-zero ground state and spin-two first excited state, which is proportional to $\cos\theta$, where θ is the angle between the neutron spin and the direction of propagation of the gamma ray, was measured to be less than one part in 10^3. From this result the conclusion is reached that the intensity of the odd-parity part of the neutron capture state is less than 2×10^{-9} times as large as the even-parity part, and that the parity-nonconserving part of nuclear forces is less than 10^{-8} times as strong as the parity-conserving part. Qualitatively similar, though weaker, conclusions were derived from the measurements on silver and indium.

I. INTRODUCTION

THE importance of a sensitive determination of the space inversion properties of nuclear forces has received emphasis from the discoveries that the weak interactions do not conserve parity.[1–3] If the nucleon-nucleon interaction Hamiltonian is divided into a parity-conserving part H and a parity-nonconserving part H', the part H will have nonvanishing matrix elements only between states of the same parity, and H' will only connect states of the opposite parity. We are concerned with the relative strength of these matrix elements. Since the parity-conserving and parity-nonconserving interactions may have different ranges and different behavior with respect to such properties as the conservation of isotopic spin, the problem is not so well defined that a numerical ratio of typical matrix elements can be more than a guide to a complete understanding of the forces which are involved. Nevertheless, at this stage of our knowledge of parity-nonconserving forces in strong interactions, order of magnitude estimates and order of magnitude experiments are useful.

Measurements of the parity impurity in states of light nuclei have been made by Tanner,[4] Wilkinson,[5–7] and Segel, Kane, and Wilkinson.[8] These measurements place an upper limit of about one part in 10^4 on the amplitude of parity impurity in various states. The relationship between these results and the strength of parity-nonconserving forces in nuclei is not explicitly stated in these papers though the plausible implication is made that the relative strength of parity-nonconserving to parity-conserving forces is also, then, less than one part in 10^4.

If the parity-nonconserving forces are quite singular, the effects of this interaction would be more easily observed in measurements on the interactions of nuclei at high energies. Measurements on the up-down asymmetry in the scattering of transversely polarized protons by Oxley *et al.*,[9,10] and Chamberlain *et al.*,[11,12] and measurements of the up-down asymmetry in π-meson production by transversely polarized protons,[10] suggest that the amplitude of the parity-nonconserving part of the interaction cannot be much larger than 10^{-2} times as great as the parity-conserving interaction, and, hence that the effective strength of the parity-nonconserving part of the nucleon-nucleon interaction, at these energies, is not more than one percent of the total interaction strength. A recent measurement on the production of π mesons by polarized neutrons suggests a still lower value of about 0.1%.[13]

The forces affecting the behavior of nuclei are the specific nuclear forces or strong interactions, characterized by a coupling constant $g^2/\hbar c\approx 1$, the electromagnetic force with a coupling of $e^2/\hbar c=1/137$; and the weak interactions with a coupling strength $f^2/\hbar c\approx 10^{-14}$. It is generally accepted as a heuristic or aesthetic principle that these classes of interactions belong to specific symmetry groups. According to such a view we would expect that if the strong interactions largely conserve parity, then they will conserve parity exactly. It is possible, however, that the approximate parity conservation in strong interactions which has been observed is accidental and that more sensitive measurements will show violations. It is also possible that there exists a specific parity-nonconserving interaction with a coupling

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strength intermediate between the electromagnetic and weak interactions. Since the weak interactions do not conserve parity, we know that there will be a small parity-nonconserving part in nuclear forces. From the virtual emission and absorption of leptons we would expect such an interaction with a strength of about $f^2/\hbar c$, or about 10^{-14}. Gell-Mann and Rosenfeld[14] point out, however, that according to one specific model of weak interactions, a nucleon may emit a virtual nucleon-antinucleon pair with a strong coupling constant $(g^2/\hbar c)^{\frac{1}{2}}$, and the pair can be absorbed by another nucleon with the weak-interaction coupling strength $(f^2/\hbar c)^{\frac{1}{2}}$. This parity-nonconserving interaction would have a strength of the order of $fg/\hbar c \approx 10^{-7}$, which might be observable. These considerations emphasize the importance of precise measurements concerning the conservation of parity in (normally) strong interactions.

II. THEORY

There are particular experimental advantages involved in detecting parity-nonconservation in nuclear forces by observing the parity impurity in specific nuclear states through measurements of transitions to or from these states.[5] If we consider the parity-nonconserving part of the nuclear Hamiltonian as a very small perturbation to the parity-conserving forces, we must, according to first order perturbation theory, expect some mixing between states of different parity. We might expect this mixing to be greatest between states which are close together as the characteristic energy denominator will be small. This, then, suggests the examination of parity impurities in the levels of heavy ncueli near the neutron binding energy where discrete levels a few electron volts apart are experimentally available.

In order to make an estimate of the effect of a parity-nonconserving perturbation on the dense highly excited levels of heavy nuclei, it is convenient to use the free-particle model of the nucleus. We shall assume that, to a first approximation, the various nucleons occupy the states of an oscillator well. The nucleus will then have excited states of energy of excitation above the ground state of $\hbar\omega$, $2\hbar\omega$, $\cdots$, of increasingly high degeneracy. This degeneracy will be removed by the two-body nucleon-nucleon interactions. It is well known that such a model can lead to level densities in heavy nuclei not very different from those which are observed.[15]

Let us then assume that the nuclear Hamiltonian, H, which described this nucleus, conserves parity. Then excited states of even parity, $\psi_{\lambda g}$, corresponding to an energy $E_{\lambda g}$, will exist. It will be a reasonable approximation to write the wave function as $\psi_{\lambda g}=\sum_i a_i u_{ig}$, where the set u_{ig} will be approximately equal to the set of N almost degenerate single-particle states belonging to the even-parity oscillator level corresponding to an energy $n\hbar\omega$, near $E_{\lambda g}$. Likewise, odd-parity states, $\psi_{\lambda u}$, will exist, where $\psi_{\lambda u}=\sum_j b_j u_{ju}$. Here the set u_{ju} represents the M single-particle levels belonging to the odd-parity oscillator level with energy $m\hbar\omega$, near $E_{\lambda u}$. For a given angular momentum there will be states of even and odd parity in any region high enough above the ground state. The density of even-parity states near $E_{\lambda g}$ will be about $N/\hbar\omega$, while the density of odd-parity states near $E_{\lambda u}$ will be about $M/\hbar\omega$. The effective values of N and M will be similar.

If a weak parity-nonconserving interaction, H', be added to H, then the states of different parity will be mixed. Let us consider the effect on the wave function $\psi_{\lambda g}$ due to the mixing of the nearest state of opposite parity, $\psi_{\lambda u}$. From first-order perturbation theory

$$\psi_\lambda=\psi_{\lambda g}+\frac{\langle\psi_{\lambda g}|H'|\psi_{\lambda u}\rangle}{E_{\lambda g}-E_{\lambda u}}\psi_{\lambda u}. \tag{1}$$

It is desirable to make an estimate of the value of the matrix element. Neglecting antisymmetrization, the functions u_{gi} represent products of A single-particle oscillator functions, where A is the number of nucleons in the nucleus. In general, for each wave function u_{gi} there will exist about A wave functions u_{uj} which differ from u_{gi} in that one nucleon is in an oscillator level one unit higher or lower than in the state occupied in u_{gi} and, hence, has different parity. If we represent the average single-particle matrix element between a nucleon in an oscillator state n and a state m as ${}_nH_m'$, and make the further plausible assumption that the interaction H' will have a form in analogy with electric dipole matrix elements such that ${}_nH_m'\approx 0$ for $|n-m|>1$, then the matrix element $\langle\psi_{\lambda g}|H'|\psi_{\lambda u}\rangle$ will be equal to the sum of NA terms, each term equal on the average to $\langle a_i\rangle_{\rm Av}\langle b_j\rangle_{\rm Av}\,{}_nH_m'$. From the normalizations of $\psi_{\lambda g}$ and $\psi_{\lambda u}$, we have $\sum_N a_i^2=\sum_M b_j^2=1$, and taking $N=M$, $\langle|a_i|\rangle_{\rm Av}\approx\langle|b_j|\rangle_{\rm Av}=N^{-\frac{1}{2}}$. Since the signs of the a_i and b_j will be random, the average value of the matrix element will be $A^{\frac{1}{2}}N^{-\frac{1}{2}}\,{}_nH_m'$. The value of the single-particle matrix element ${}_nH_m'$ would appear to be a reasonable measure of the strength of parity-nonconserving forces. This should then be compared with a value of ${}_nH_n$, the single-particle matrix element for parity-conserving forces which will be of the order of the nuclear well depth, or about 40 Mev.

The average value of the denominator in Eq. (1), $E_{\lambda g}-E_{\lambda u}$, will be equal to the average level spacing, $\hbar\omega/N$. Using this value and the estimate which was made of the matrix element $\langle\psi_{\lambda g}|H'|\psi_{\lambda u}\rangle$, we can write Eq. (1) as

$$\psi_\lambda=\psi_{\lambda g}+\frac{A^{\frac{1}{2}}N_n^{\frac{1}{2}}H_m'}{\hbar\omega}\psi_{\lambda u}. \tag{2}$$

We can estimate the value of $\hbar\omega$, using the relation $\hbar\omega=(\hbar^2M^{-2}R^{-2}V)^{\frac{1}{2}}$ where M is the nucleon mass, R the nuclear radius, and V the well depth. If we take a

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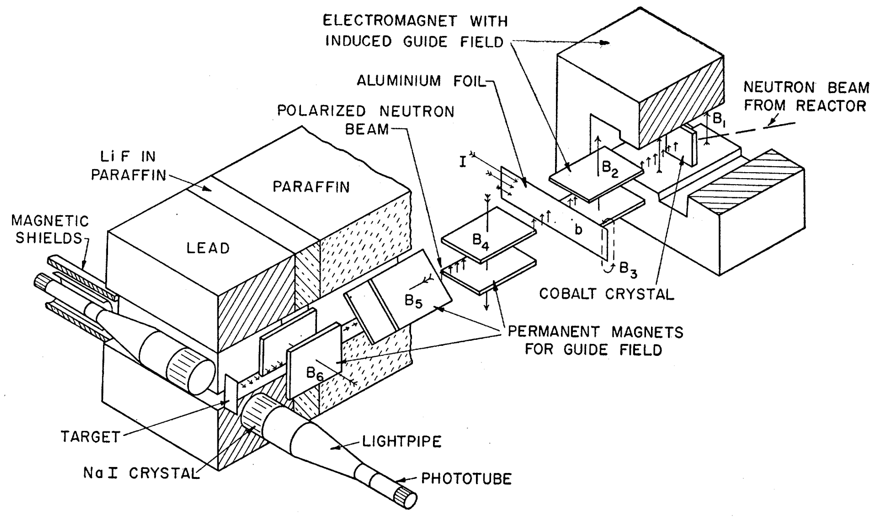

FIG. 1. Schematic diagram showing the disposition of the experimental equipment.

typical level spacing of 20 electron volts in a nucleus of $A=100$, we find an amplitude parity impurity of 10^{-3} for an interaction strength of one electron volt.

Measurement of the parity impurity in such levels is easily accomplished by observing asymmetries in the emission of capture γ rays from polarized states. Consider, for example, a gamma-ray transition to a spin-$\frac{1}{2}$ even-parity state, following the capture of a slow polarized neutron by an even-parity spin-zero nucleus. If the parity admixture in the compound state is small, magnetic dipole radiation will predominate. Due to the parity impurity, electric dipole radiation will also be emitted. These radiations will be coherent, and the angular distribution of the emitted intensity will be proportional to $1+A\cos\theta$, where

$$A=2\,\mathrm{Re}[E^*M(E^2+M^2)^{-1}].$$

In this relation θ represents the angle between the gamma ray and the neutron polarization direction, and E and M are the amplitudes of the electric and magnetic dipole radiation, respectively. If the parity-nonconserving interaction H' is invariant under time reversal, E and M will be relative real.[16,17] For other spins of the initial and final states, the function A will be multiplied by a statistical factor with a value smaller than one.

III. EXPERIMENTAL PROCEDURE

The determination of the extent of parity mixture in some highly excited states of nuclei was made by measuring the asymmetry of the γ-ray emission after the capture of polarized slow neutrons. The angular distribution of the gamma rays would be expected to be proportional to $1+A\cos\theta$, where A is the measure of parity mixing, and θ is the angle between the spin of the neutron and the direction of propagation of the gamma ray. The magnitude of A was conveniently measured by observing the difference between the intensity of specific transitions at $\theta=0$, and at $\theta=\pi$.

A schematic representation of the equipment used in the measurements is shown in Fig. 1. A neutron beam, from the Brookhaven reactor, with a mean energy of 0.09 ev was incident upon a single cobalt crystal, $1\frac{1}{2}$-in.$\times 1\frac{1}{4}$-in.$\times\frac{1}{4}$-in. in size, which was held in the jaws of an electromagnet. The configuration of the crystal, which consisted of 94% cobalt and 6% iron, was face-centered cubic. Bragg-reflected neutrons from the (111) plane of the crystal are polarized in the direction of the magnetic field.[18,19] These neutrons passed through guide fields, which conserve the magnitude and control the direction of the polarization until the neutrons pass into the target material. The guide field of about 100 gauss, which was produced by sections of permanent magnets, was rotated through 90° about the axis of neutron propagation so that the neutron spin at the target was horizontal and perpendicular to the beam direction. The direction of polarization was rotated solely for convenience. Appropriate shielding of the NaI scintillation crystals and their associated photomultipliers, which were used to detect and measure the γ rays, was more easily accomplished where the detectors could be placed horizontally, as shown in Fig. 1.

Values of A were determined by measuring the ratio of the intensity at $\theta=0$, and at $\theta=\pi$ radians. It appeared to be simpler to change the direction of polarization of the neutrons rather than to rotate the detectors about 180°. The reversal of the neutron spin could easily be obtained by reversing all of the magnetic fields. Since any effect on the gain of the photomultipliers

[16] The radiative capture of S-wave and $P^{\frac{1}{2}}$-wave π mesons by nucleons has some formal similarities to the above considerations. The discussions by Watson of the role of time reversal in determining phases in π-nucleon photoproduction is essentially applicable. K. M. Watson, Phys. Rev. **95**, 228 (1954).

[17] The measurement of the dipole moment of the neutron places a limit of about 10^{-7} on the possible strength of a parity-nonconserving interaction which is not invariant under time reversal. E. M. Purcell and N. M. Ramsey, Phys. Rev. **78**, 807 (1950); L. Landau, Nuclear Phys. **3**, 127 (1957).

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resulting from such a variation of the field direction would result in a change of the counting rate and a spurious value of A, it seemed desirable to maintain the guide fields near the target, and hence near the photomultiplier tubes, unchanged. It was possible to do this by following a method used by Dabbs.[20]

In one mode, the direction of the magnetic field in the electromagnet is down, or opposite to the direction shown in Fig. 1. The spin direction of the polarized neutrons will also be down. In this mode there will be no current through the aluminum foil, and the neutron spin direction will follow the direction of the permanent magnet guide fields. For the reversed mode, illustrated in Fig. 1, the current in the electromagnet is reversed, the field is up and the spins of the polarized neutrons are up. A current of 400 amperes is passed through the aluminum foil which is about 0.35 mm thick and 6 cm wide. Before entering the foil the neutrons are precessing about a field in the direction of their spins. After passing through the foil the neutrons are precessing about a field opposite to their spins. Since the change in field direction is made in a time which is small compared to the precession frequency, there is no depolarization of the neutrons. Again, the permanent magnet guide fields rotate the polarization direction until it is horizontal at the target. The magnitude of the polarization direction until it is horizontal at the target. The magnitude of the polarization was determined to be about 80% in each mode by measuring the Bragg scattering from the (220) plane of a calibrated magnetite crystal held in a permanent magnet.

The capture γ rays were detected by two NaI crystals 3 in. in diameter and 3 in. deep, subtending solid angles of about 0.25 steradian at the target. Light from the crystals passed through Lucite light pipes 12 in. long to photomultipliers. Pulses from the photomultipliers were amplified and fed into single-channel pulse-height amplifiers.

Magnetic shields consisting of two concentric iron pipes and a mu-metal cylinder guarded the photomultiplier tube from the effects of the changing stray fields from the electromagnet which was about three feet away. The change in gain caused by the reversal of the field was shown to be less than 3 parts in 10^4 by measuring the variation in counting rate in a narrow channel set on the side of a γ-ray peak from a source.

The crystals were shielded from room backgrounds of neutrons and γ rays with lead, LiF and paraffin, and with paraffin. Neutrons scattered from the target were shielded from the crystal by thin boron-loaded foils. With this shielding, about 3 background counts per minute were recorded corresponding to energies between 8 Mev and 9.5 Mev. The flux of 20 000 neutrons per second on an area of about a square inch gave a counting rate in the same energy interval, with a cadmium target, of about 15 counts per minute. This was the lowest counting rate used in the experiment.

High-energy transitions from thermal neutron capture states in cadmium, indium, and silver were measured. The reasonably accurate energy calibration required was obtained by measuring the pulse-height spectrum resulting from capture of the neutron beam in iron. Kinsey and Bartholomew[21] have measured the energy of the ground-state transition in Fe^{57} resulting from neutron capture by Fe^{56} to be 7.639 ± 0.004 Mev. The three peaks resulting from the capture of all the energy in the crystal, from the loss of one annihilation γ ray from pairs which were produced, and from the loss of both gamma rays, were easily resolved and served as energy calibration points.

IV. RESULTS AND CONCLUSIONS

From the previous arguments, we have concluded that a particularly sensitive measure of the effect of parity-nonconserving forces can be made by determining the asymmetry of gamma rays following the capture of polarized neutrons to form a compound state of a nucleus in which the level density is high. It is also desirable that transitions in which the impurity state is favored be chosen, such as transitions involving a spin change of one and (nominally) no change in parity. In this case the regular transition will procede by magnetic dipole radiation while the parity impurity will induce an electric dipole transition. This will result in an enhancement of about an order of magnitude.[22,23] Transitions involving small values of the spins of the compound state and the final state are preferable, as the statistical factors are then larger. For reasons concerning experimental facility, it was necessary to choose transitions which were not masked by high-energy gamma rays connecting other states. It was also necessary that the product of the thermal neutron cross section and the partial width for the selected transition should be sufficiently large to produce a reasonably large gamma-ray intensity.

The only target material which seemed to fulfill the above requirements ideally was cadmium; however, measurements were also made using silver and indium.

The neutron absorption cross section of cadmium is about 3500 barns[24] at 0.1 ev. Virtually all of this is the result of capture in Cd^{113} to form a spin-one state[25] of Cd^{114}. From the shell model we know that Cd^{113} has even parity and hence that the Cd^{114} state has (nominally) even parity as S-wave neutrons will be captured. Although the Cd^{114} state decays predominantly to highly

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[21] B. B. Kinsey and G. A. Bartholomew, Phys. Rev. **89**, 375 (1953).

[22] J. M. Blatt and V. F. Weiskopf, *Theoretical Nuclear Physics* (John Wiley and Sons, New York, 1952), See 12.

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[25] B. B. Kinsey and G. A. Bartholomew, Can. J. Phys. **31**, 1051 (1953).

excited states[26] of Cd^{114}, there is an appreciable intensity of radiation to the spin-zero ground state and spin-two first excited state. The 9.05-Mev ground-state transition takes place about 1.4×10^{-3} times per neutron capture, while the 8.48-Mev transition to the first excited state takes place with a frequency of about 2.3×10^{-3} times per capture.

Measurements of the asymmetry were made at two different settings of the single-channel analyzers. One measurement was made with the channel set to accept energy losses in the crystal from 7.6 to 9.1 Mev. The intensity recorded was then about 50% from the ground-state transition and about 50% from the transition to the first excited state. The measured value of the asymmetry parameter A was $(4.2\pm6.5)\times10^{-4}$. A measurement, accepting γ rays of energies from 8.3 to 9.3 Mev, resulted in a value of A of $(1.2\pm7.8)\times10^{-4}$. This can be considered a measure of the asymmetry of the ground-state transition. From this result we conclude that the amplitude of the electric dipole transition to the ground state was less than or equal to 4×10^{-4} times the magnetic dipole amplitude, and, using an enhancement figure of 10 for the electric dipole, we conclude that porportion of the amplitude of the odd-parity admixture in the highly excited spin-one state formed by the neutron capture is less than or equal to 4×10^{-5}, or the intensity of the odd-parity part is less than or equal to about 1.6×10^{-9} times that of the even-parity part. From Eq. (2) and the values of the parameters A, N, and $\hbar\omega$ presented in the discussion of Eq. (2), we then place an upper limit of 0.04 electron volt for the value of ${}_nH_m'$. It is perhaps appropriate to compare this value of the strength of parity-nonconserving interaction with the nuclear well depth of about 4×10^7 ev and conclude that the strength of parity-nonconserving forces in nuclei is less than 10^{-8} times the strength of parity-conserving forces, allowing then a factor of ten for the uncertainties involved.

Similar measurements were made on the asymmetry of gamma rays following the capture of polarized neutrons in silver and indium. Neutrons captured by silver form states of Ag^{108} and Ag^{110} with odd parity and spins of zero or one. We investigated the asymmetry of the 7.27-Mev gamma ray resulting from the transition to the ground state of Ag^{108}. The value of the parameter A was measured to be $(-0.3\pm1.2)\times10^{-3}$. In this case the impurity must result in a proportion of magnetic dipole radiation amplitude of $(1.5\pm6)\times10^{-4}$. Since the magnetic dipole transition is intrinsically unfavored by about a factor of 10, we estimate the proportion of parity impurity amplitude in the capture state to be $(1.5\pm6)\times10^{-3}$. This value, assuming the transition is primarily the result of a spin-one state, leads to an upper limit of the value of the strength of parity-nonconserving forces, ${}_nH_m'$, of about 5 electron volts. The restriction is weaker to the extent that the transition is the result of a capture into a spin-zero state.

Neutrons captured by indium form a spin-4 or spin-5 state of In^{116} with odd parity. Transitions to the spin-zero ground state or spin-two first excited state must be extremely weak. We measured the asymmetry coefficient A for the gamma rays with energies above 5.6 Mev. These gamma rays probably represent a mixture of dipole transitions from the capture state to relatively high-lying states of even parity and spins of 3, 4, and 5, together with some cascading gamma rays. The measured value of A was $-(2.5\pm4)\times10^{-3}$. It is necessary to assume, as in the case of the silver measurement, that the impurity transition was unfavored. Noting also that the large values of the spins involved result in a reduced statistical factor, we estimate that the limit placed on the value of ${}_nH_m'$ by this experiment is about 50 electron volts.

It is desirable to emphasize again that the conclusion reached in this work, that the strength of parity-nonconserving forces in the nucleus is less than 10^{-8} times as strong as the parity-conserving forces, is the result of estimates which are statistical in nature and furthermore applies literally to specific models of the nucleus. While it seems probable that no serious error in the numerical conclusion will result, this numerical conclusion is to be considered primarily as an order-of-magnitude estimate. This estimate does not then preclude the existence of parity-nonconserving weak interactions involving a four-baryon vertex as suggested by Gell-Mann,[14] though the limit set here is 10^{-8} while the order-of-magnitude estimate of the Gell-Mann interaction is 10^{-7} times the strong-interaction strength. However, it seems quite unlikely that any stronger parity-nonconserving interaction exist, and in particular this result suggests that the coupling of the nucleon to the K-meson field is such as to conserve parity.

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