New results on the violation of p-parity in proton-proton and nucleon-nucleus interactions

V. B. Kopeliovich

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1. EXPERIMENTAL DATA

Exceptionally important results were published recently[1-4] on the violation of spatial partiy in proton-proton and proton-nucleus interactions in a broad range of energies (up to 6 GeV/c). Parity violations in nuclear processes have been studied for seventeen years since the discovery—in 1964—of P-odd nuclear forces in the $n\gamma$-reaction on ^{113}Cd. Experimental investigations of P-odd effects in such processes (which include, in addition to $n\gamma$-reactions, effects such as radiative transitions in nuclei, alpha decay, and fission induced by polarized neutrons) have been facilitated by the fact that reactions on sufficiently heavy nuclei involve specific mechanisms (as a rule, the mixing of closely lying levels of opposite parity) that amplify the observed effects to values of the order of 10^{-5}–10^{-4} or, in some cases, even higher values (see, for example, Refs. 6–8). However, attempts to detect parity violations in direct expeeriments on nucleon-nucleon or nucleon-nucleus scattering have not been successful because the P-odd effects are very small in such processes. For pp scattering, only the upper limit has been available[9] for the P-odd asymmetry $A=(\sigma_+-\sigma_-)/(\sigma_++\sigma_-)$ where $\sigma_\pm$ are the total cross sections for the scattering of protons with polarization parallel (antiparallel) to their momentum.

The values reported in Refs. 1 and 2 for A_{pp} at proton energies of 15 MeV (LASL) and 45 MeV (SIN) are as follows:

$$A_{pp}\,(15\ \text{MeV}) = (-1.7 \pm 0.8)\cdot 10^{-7},$$
$$A_{pp}\,(45\ \text{MeV}) = (-3.2 \pm 1.1)\cdot 10^{-7}.$$

In the case of pd scattering at 15 MeV, the upper limit is known[10] to be

$$A_{pd}\,(15\ \text{MeV}) = (-0.35 \pm 0.85)\cdot 10^{-7}.$$

At the Argonne National Laboratory, the proton-water asymmetry at 6 GeV/c was found to be

$$A_{pH_2O}\,(5\ \text{GeV}) = (2.65 \pm 0.60)\cdot 10^{-6}.$$

This result means that the P-odd effects in the proton-nucleon interaction increase substantially with increasing energy.

The rotation of the spin of a neutron polarized at right angles to its momentum in tin has also been measured.[4] This striking effect was noted in Ref. 11 and is analogous to the rotation of the plane of polarization of photons in bismuth vapor.[12] It is due to the fact that the phase of the neutron wavefunction that is acquired when the neutron is scattered by the nucleus depends on the component of the spin in the direction of the momentum. The factor $\exp(i\mathbf{k}\cdot\mathbf{x})$ for the neutron is replaced in the medium by $\exp(in\mathbf{k}\cdot\mathbf{x})$, where the refractive index is given by $n=1+(2\pi/k^2)\rho f(0)$. The amplitude for scattering through zero angle by an atom of the medium is $f(0)=f^+ + f^-\sigma_n\mathbf{k}$ where ρ is the density of the medium (number of atoms per unit volume). The operator $\exp(-\frac{1}{2}i\varphi\sigma_n\mathbf{k})$ represents rotation of the neutron spin through the angle $\varphi=-4\pi\rho L\,\mathrm{Re}f^-$ about the direction of $\mathbf{k}$, after the neutron has traversed a distance L. The angle φ corresponding to a distance of 1 cm in tin has been measured[4] at neutron energy of about 0.01 eV ("cold" neutrons). The result is

$$\varphi\,(^{117}\text{Sn}) = (+36.7 \pm 2.7)\cdot 10^{-6}\ \text{rad/cm},$$
$$\varphi\,(^{124}\text{Sn}) = (+0.48 \pm 1.49)\cdot 10^{-6}\ \text{rad/cm}.$$

For natural tin

$$\varphi\,(^{\text{nat}}\text{Sn}) = (+4.95 \pm 0.93)\cdot 10^{-6}\ \text{rad/cm}.$$

When the contribution due to ^{117}Sn (7.61%) in natural tin is subtracted from the last number, the remainder is $\varphi' = (+2.16 \pm 0.93)\times 10^{-6}$ rad/cm. The positive sign shows that the rotating spin of the neutron and its momentum form a right handed screw. This effect is, of course, determined by the real part of the amplitude that does not conserve parity.

The dependence of the total neutron scattering cross section of tin on the neutron spin has also been measured[4] but with a much greater uncertainly. The result is $A_{n\text{Sn}}=(-9.78\pm 4.01)\times 10^{-6}$. This effect is determined by the imaginary part of the amplitude that does not conserve parity. Since the weak amplitude is

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real, there is an appreciable contribution due to the term describing interference between weak and strong interactions in the total amplitude for the scattering of neutrons by tin.

More accurate measurements of A_{nSn} at the Leningrad Institute of Nuclear Physics have shown that $A_{nSn} = (-6 \pm 1)\times 10^{-6}$ at neutron energies of about 0.02 eV.

2. THEORETICAL ESTIMATES AND UNCERTAINTIES

According to existing ideas, P-odd effects in hadron interactions conserving strangeness (flavor) are due to interference between the parity-violating weak-interaction amplitude and the strong-interaction amplitude that determines the observed hadron scattering cross section.

Measurements of the aymmetry of the total pp scattering cross section at 15 and 45 MeV agree to within an order of magnitude with the estimate based on simple considerations:

$$A_{pp} \sim \frac{Gm^2}{4\pi} \sim 10^{-7};$$

where $G \simeq 1.2\times 10^{-5}$ GeV^{-2} is the Fermi weak-interaction constant and m^{-1} is the characteristic size for weak interactions; at sufficiently high energies, i.e., $m \simeq 0.3$ GeV, the quantity m is found to decrease with decreasing energy.

More detailed calculations of A_{pp} performed by a number of workers[13-16] have reproduced the order of magnitude of the effect, but do not completely agree with one another. At high energies, they take into account only the parity violating $^1S_0 \to {}^3P_0$ transition, with the transition amplitude calculated with allowance for the interaction in the intial and final states being proportional to

$$f_{^1S_0 \to {}^3P_0} e^{i(\delta_{^1S_0} + \delta_{^3P_0})},$$

where $\delta\ {}^1S_0$ and $\delta\ {}^3P_0$ are the $^1S_0$ and $^3P_0$ scattering phases and the cross section asymmetry is

$$A_{pp} = \frac{2kf_{^1S_0 \to {}^3P_0} \sin(\delta_{^1S_0} + \delta_{^3P_0})}{\sin^2\delta_{^1S_0} + \sin^2\delta_{^3P_0} + 3\sin^2\delta_{^3P_1} + 5\sin^2\delta_{^3P_2}}.$$

The total pp cross section in the denominator of this expression is given in terms of the scattering phases. The real amplitude $f\ {}^1S_0 \to {}^3P_0$ includes contributions due to isoscalar or isotensor weak interactions (exchange of vector mesons; Fig. 1a) as well as the isovector weak interaction (exchange of at least two pions (Fig. 1b, c) and also a neutral vector meson; we recall that the parity violating π^0NN vertex is forbidden by CP invariance). The contribution of vector exchanges to A_{pp} with the constants ρ^0NN and ωNN calculated in accordance with the Weinberg-Salam model, including the gluon corrections, yield[16] a

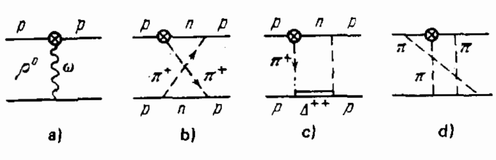

FIG. 1.

value for A_{pp} that is several times smaller than the observed value.[1,2] It is therefore important to investigate and calculate the isovector contributions to the cross section asymmetry which, according to existing estimates, are of the order of 10^{-7} (in the Weinberg-Salam model[13,14]). The simplest diagrams of Fig. 1b, c do not exhaust all the possible diagrams for the isovector weak interaction: there are also irreducible diagrams for three pion exchanges (Fig. 1d), and so on.

The isovector weak interaction, i.e., charged-pion exchange, plays an important role in radiative transitions in nuclei.[8] Existing experimental data indicate that the weak interaction constant $g^W_{\pi NN}$ lies in the range[8] $(0.3-0.6)\times 10^{-6}$. The theoretical value of this constant is subject to considerable uncertainty because symmetry considerations alone are not sufficient for its calculation, and dynamic assumptions must be introduced to calculate the contributions due to virtual $q\bar{q}$ pairs.[17] Nevertheless, it is important to note that the value of this constant in theories with neutral currents may be greater than in the Cabbibo theory in which[17] $g^W_{\pi NN} \sim \sin^2\theta_C$, $\sin^2\theta_C \simeq 1/25$, and $g^W_{\pi NN} \simeq 4\times 10^{-8}$.

The fact that the ratio of real to imaginary strong-interaction amplitudes, $\eta = \mathrm{Re}f/\mathrm{Im}\,f$, is small must be taken into account at high energies, since the real weak amplitude interferes in the cross section with the real part of the strong-interaction amplitude. Hence

$$A_{pN} \sim |\eta| \frac{Gm^2}{4\pi} \approx 3\cdot 10^{-8}$$

at 6 GeV/c. More detailed calculations, performed in the parton model with charged currents, and taking into account the component-quark exchanges,[18] yields a somewhat lower result: $A_{pN} \simeq 10^{-8}$. Inclusion of the contributions due to neutral currents cannot raise the theoretical value of A_{pN} above 3×10^{-8}. There is thus a discrepancy amounting to two orders of magntiude between the experimental value of A_{pN} and the theoretical prediction based on the parton model.[1)]

Detailed calculations of the rotation of the neutron spin in tin have not been possible because they would require a knowledge of the structure of the nuclear levels, their quantum numbers, and the corresponding wavefunctions. Estimates have shown[19] that the observed effect exceeds by a factor of 3000 the value of φ that is obtained when the amplitude for the neutron-tin interaction is taken to be the sum of the amplitudes for the neutron-electron and neutron-nucleon interactions in the Weinberg-Salam model. The necessary enhancement can be achieved if ^{117}Sn is assumed to have a sufficiently closely lying p-level (at a separation of about 1 eV).[19] The necessary enhancement factor can be less than 3000 if the elementary interaction is taken to be the isoscalar ineraction (two-pion exchange) which has a greater effective interaction constant. Moreover, calculations performed for ^{18}F: ^{19}F, ^{21}Ne, ^{41}K, ^{175}Lu, and ^{181}Ta have shown that enhancement

[1)]Glauber screening does not alter the result significantly for the ^{16}O nucleus and has been neglected in making these estimates.

factors of about 100 or more are readily possible. For example, in ^{19}F, the experimental asymmetry obtained for the emitted photons[20] is $A_\gamma = (-0.85 \pm 0.26)\times 10^{-4}$ whereas the theoretical value is -1.5×10^{-4}; in ^{175}Lu, the circular polarization of photons is[21] $P_\gamma^{exp} = (0.55+0.05)\times 10^{-4}$ whereas the theoretical value[8] is 0.56×10^{-4}. There are also effects that are much stronger. For example, in ^{180m}Hf, the observed value of A_γ is[22] $(1.66\pm 0.18)\times 10^{-2}$ but, because the nuclear structure is not adequately known, sufficiently reliable theoretical values are not available.

3. THE SITUATION WITH THE *P*-ODD EFFECT OBSERVED IN $np\to d\gamma$ CAPTURE

Let us now briefly consider the *P*-odd effects in np $\to$ dγ capture, since this elementary nuclear process has given rise to a discrepancy that has persisted for many years between the observed circular polarization of photons[23] $(-1.3+0.45)\times 10^{-6}$ and nonrelativistic calculations[8,24] that yield $P\gamma = (2-3)\times 10^{-8}$. New measurements of circular polarization in the np$\to$dγ reaction are in progess at the Leningrad Institute of Nuclear Physics, using substantially modified appratus. The experimental precision should be sufficient to enable us, in the near future, to improve on the result reported previously.

The *P*-odd effects that occur in this reaction during thermal-neutron capture are due to interference between the main magnetic dipole transition from the $^1S_0$ state and the amplitude of the E1 transition from the $^1S_0$ state (in the case of circular polarization $P\gamma$) or the $^3S_1$ state (in the case of the asymmetry $A\gamma$ in the emission of photons accompanying the capture of a polarized neutron). The isospin selection rules for these quantities in the nonrelativistic treatment are as follows: $P\gamma$ is determined by the isoscalar or isotensor part of the weak Hamiltonian, i.e., by heavy vector meson exchange; the asymmetry is determined by the isovector part of the weak Hamiltonian, i.e., by light-pion exchange.[24] The reduction in the nonrelativistic result for $P\gamma$ is due to both repulsion between nucleons at distances $\sim 1/m_V$, where m_V is the mass of the vector meson, and the fact that the nonrelativistic operator for the electric dipole transition is of the form ωr, i.e., it is proportional to the (small) energy of the photon ($\omega = \varepsilon = 2.2$ MeV). Relativistic effects (mainly nonmass effects) modify the isospin selection rules, so that $P\gamma$ acquires a contribution due to the isovector part of the weak Hamiltonian (correspondingly, the isoscalar part of the electromagnetic interaction).[25] A rough estimate of the relative magnitude of these contributions in the case of $P\gamma$ is

$$\frac{\varepsilon}{M}\frac{g^{W}_{\pi NN}g^{S}_{\pi NN}}{\mu_\pi^2+P^2}\frac{P^4}{m^4}\left(\frac{g^{W}_{VNN}g^{S}_{VNN}}{m_V^2}\sqrt{\frac{\varepsilon}{M}\frac{P^2}{m_V^2}}\right)^{-1}\sim 1,$$

where $g^{W}_{VNN} = 5\times 10^{-7}$, M is the nucleon mass, and P is the momentum of a nucleon in the interior of the nucleus. The small values $(\varepsilon/M)^{1/2}\simeq 1/20$ and $P^2/m_V^2 \simeq 0.2$ in the denominator of this expression are due to the factor ω in the operator for the electric dipole transition and to repulsion at short distances. Relativistic effects are of the order of ε/M and are partially compensated by the small denominator, but are not accompanied by any other appreciable small quantities. This is so because for the isoscalar electromagnetic interaction and the isovector weak interaction (and only in the case of spatial parity violation!) we have diagrams such as those given in Figs. 2a, b, which contribute to the zero component of the effective current, so that

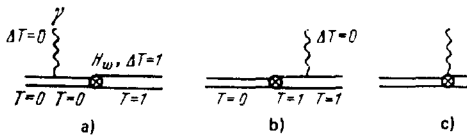

FIG. 2.

$$j_\alpha \approx C\left(\xi_\alpha - \frac{d_\alpha}{dq}\xi q\right),$$

where $C\sim\varepsilon$ due to the compensation of the diagrams in Figs. 2a and b, ξ is the deuteron wavefunction, and d is the 4-momentum in the initial or final states. These pole contributions are absent in the case of the isovector electromagnetic interaction. More detailed evaluation of the relativistic contributions shows that they are of the order of 10^{-6}. In the case of the asymmetry $A\gamma$, the long-range amplitude of the single-pion exchange is found to provide a contribution even in the nonrelativistic approxomation, so that relativistic effects must be weaker. Experiment[26] shows that $A\gamma = (0.6+2.1)\times 10^{-7}$, which is not inconsistent with existing theoretical estimates.[8]

The nuclear-quark approach[27] is an alternative to the approach based on meson exchange. The advantge of the former in calculations of the contribution of the isoscalar weak interaction (vector exchange) is that one avoids the calculation of the coupling constants between the vector mesons and the nucleons, since the amplitude is expressed directly in terms of the coupling constants between the intermediate bosons and the quarks, and the distribution of quarks in the deuteron at short distances. We note, however, that the gauge invariant switching-on of the electromagnetic interaction in this approach is technically much more difficult that for the two-nucleon system[25] and requires separate examination.

4. FUTURE DEVELOPMENTS AND PROBLEMS

The experiments briefly reviewed above signal the completion of what is essentially a new branch of the physics of weak interactions—the weak interaction of hadrons without change in strangeness (flavor)—which began with the experiments on *P*-odd nuclear forces. Clearly, there are still many problems that must-and undoubtedly soon will—be resolved.

Apart from the need for a more accurate value of the *P*-odd asymmetry of the total cross section for the pp interaction, and for a verification of the circular polarization in np$\to$ dγ capture, it would be very desirable to repeat the experiment at 6 GeV/*c* and, if the result is confirmed, to determine the energy dependence of the effect from about 45 MeV up to momenta of the order of 6 GeV/*c* and higher. It would also be desirable to perform more complex experiments, e.g., measurements of correlations of the form

$$\langle [\boldsymbol{\zeta}_p \times \boldsymbol{\zeta}_t]\, \mathbf{k}_0 \rangle,$$

where ζ_p and ζ_t are the beam and target spins, respectively.[18] This effect is proportional to the imaginary part of the amplitude for the strong interaction and may be of the order of 10^{-5} if $A_{pN} \sim 3\times 10^{-6}$. Confirmation of parity violations of this order may well lead to a modification of current ideas on weak (and, possibly, even strong) interactions between hadrons at high energies.

Independently of all this, it would be interesting to look for single (weak) production of strange particles, in the first instance hyperons, i.e., reactions of the form[28] $pN \to N\Lambda$, $N\Sigma$. In standard theories, the cross sections for these reactions are of the order of 10^{-39} cm^2 at proton energies of 0.6–0.8 GeV, and decrease with increasing energy down to $\sim 10^{-40}$ cm^2. If the mechanism responsible for the enhancement of the weak hadron-hadron interaction at high energies can be extended to these processes as well, then the corresponding cross sections may be higher by 3–4 orders of magnitude.

Processes occuring at low energies are very complicated from the theoretical point of view. At intermediate energies, the theory of elemntary particles is still far from the stage where one could seriously compare experimental results with theoretical predictions. One of the important tasks is to investigate the isovector weak interaction between nucleons due to single-or many-pion exchange (cf. Figs. 1b–d). It is known that analogous processes play an important role in the strong interation between nucleons at intermediate energies.[29] As indicated above, there are grounds for supposing that these processes play a determining role even in the weak interaction and, in particular, in pN scattering at about 1 GeV, as well as in radiative processes in nuclei, including $np \to d\gamma$ capture. The development of the theory of the weak interaction between hadrons cannot proceed without advances in the theory of strong interaction and, conversely, studies of the weak interaction between hadrons may lead to a new point of view in relation to the strong interaction problem.

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