of about 10^{-2} (in contrast to the estimated[8] upper limit of 10^{-4} for the lepton-conservation-violating interaction in double β decay).

Note added in proof.—A preliminary analysis of the experiment in progress[4] indicates that the ratio $\mathcal{R}^{\exp}$ will be tested to a value between 1×10^{-9} and 1×10^{-10}.

The author would like to thank Dr. K. Gotow and Dr. P. Herczeg for helpful discussions, and Professor H. Primakoff and Professor L. Wolfenstein for reading the manuscript.

*Work supported in part by the National Science Foundation.

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Possible Time-Reversal Noninvariance in Nuclear Forces*

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(Received 16 February 1971)

A model suggested by Sudarshan which relates strong, weak, and electromagnetic interactions through vector and axial-vector currents is adapted to nucleon-nucleon scattering. Strong time-reversal violation is predicted in n-p scattering above 100 MeV through the same mechanism assumed to cause CP-invariance violation in weak hadronic decays. Where a T-invariance violation has been sought for and not found, i.e., in p-p scattering up to 635 MeV and low-energy n-p scattering, the model predicts very little T-invariance violation.

Sudarshan has suggested a model for strong, weak, and electromagnetic interactions which violates CP invariance in strong interactions.[1] Assuming that CPT invariance holds, T invariance is likewise violated. At first sight, it would seem unreasonable to suggest such a model when all experiments in strong interactions to date indicate very little time-reversal invariance violation (TRV), consistent with zero. However, it is possible that experimentalists have been looking in the wrong places. We have extended Sudarshan's model, in a manner to be described shortly, in order to get accurate predictions for nucleon-nucleon scattering and find that in p-p scattering, T invariance is only slightly violated from 0 to 635 MeV, and in n-p scattering, T-invariance violation is likewise slight below 100 MeV. The only place strong violation occurs is in n-p scattering above 100 MeV, but here there are no experimental measurements. If the mod-

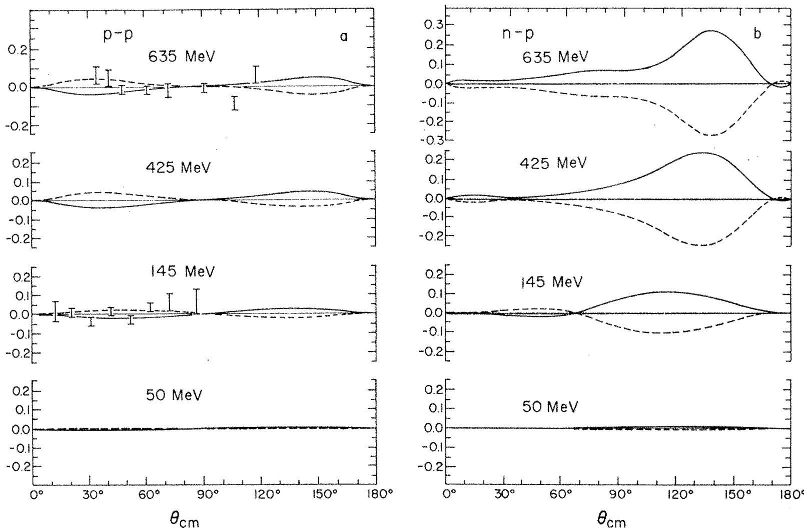

FIG. 1. Graphs of polarization minus asymmetry ($P-\mathcal{a}$) predicted by the extended one-boson-exchange model described in the text, at $T_{lab}=50$, 145, 425, and 635 MeV. The solid and dashed curves correspond to taking f_A equivalent to plus and minus $(4M/2m_A)g_A$, respectively (see text). The p-p data at 142 and 635 MeV are taken from Ref. 2.

el's predictions are correct the T-invariance violation should be easy to detect. A difference in n-p polarization and asymmetry is predicted which may be as great as 0.28 at 635 MeV (see Fig. 1).

Sudarshan[1] assumes that neutron β decay is mediated by ρ and $A_1(1070)$ exchange with the ρ responsible for the vector interaction and the A_1 responsible for the axial-vector interaction. The Born terms for the two exchanges are

$$4\pi\sqrt{2}g_\rho[\bar{u}(p)\gamma_\mu\tau^+u(n)](m_\rho^2-q^2)^{-1}[\bar{u}(e)\gamma_\mu(1+\gamma_5)u(\nu_e)]G'm_\rho^2$$

and

$$4\pi\sqrt{2}g_A[\bar{u}(p)\gamma_5\gamma_\mu\tau^+u(n)](m_A^2-q^2)^{-1}[\bar{u}(e)\gamma_\mu(1+\gamma_5)u(\nu_e)]G'm_A^2,$$

respectively. Imposing the $V-1.18A$ rule requires that

$$g_\rho G'=G_V \tag{1a}$$

and

$$g_AG'=-G_A=1.18G_V, \tag{1b}$$

where G_V is the universal weak-interaction coupling constant. To get the required ratio, $g_A/g_\rho=1.18$, Sudarshan assumes that the ρ and A_1, along with the $D(1250)$ meson $(T, J^P=0, 1^+)$, are coupled to the $N(938)$ and $\Delta(1236)$ in an SU(4) scheme. The strong-interaction Lagrangian is

$$\mathcal{L}_1^{\text{int}}=(4\pi)^{1/2}\bar{\psi}[g_\rho\gamma_\mu\vec{\tau}\cdot\vec{\rho}_\mu+g_A\gamma_5\gamma_\mu\vec{\tau}\cdot\vec{A}_\mu+(f_A/4M)\gamma_5\sigma_{\mu\nu}\vec{\tau}\cdot\vec{A}_{\mu\nu}+g_D\gamma_5\gamma_\mu D_\mu+(f_D/4M)\gamma_5\sigma_{\mu\nu}D_{\mu\nu}]\psi, \tag{2a}$$

where $A_{\mu\nu}=\partial_\nu A_\mu-\partial_\mu A_\nu$ and similarly for $D_{\mu\nu}$. The derivative coupling of the A_1 is introduced somewhat arbitrarily, and set equal to the direct coupling (apart from mass factors) to bring about an extra factor of $2^{-1/2}$ in the ratio of G_A to g_ρ, so that $g_A=\frac{5}{3}\times2^{-1/2}g_\rho\simeq1.18g_\rho$, the desired value. However, having both direct and derivative coupling brings about C-invariance violation, as the vector and tensor currents transform differently under C. P is conserved, so CP and T invariances are violated by the Lagrangian of Eq. (2). Other coupling constants predicted by the SU(4) scheme are $f_A=(4M/2m_A)g_A$, $g_D=2^{-1/2}g_\rho$, and $f_D=(4M/2m_D)g_D$.

Sudarshan links the ρ to the φ meson by a second SU(4) coupling. The additional interaction Lagrangian is

$$\mathcal{L}_2^{\text{int}}=(4\pi)^{1/2}\bar{\psi}[(f_\rho/4M)\sigma_{\mu\nu}\vec{\tau}\cdot\vec{\rho}_{\mu\nu}+(f_\varphi/4M)\sigma_{\mu\nu}\varphi_{\mu\nu}+g_\omega\gamma_\mu\omega_\mu+(f_\omega/4M)\sigma_{\mu\nu}\omega_{\mu\nu}]\psi, \tag{2b}$$

where $f_\rho = \frac{5}{3}(4M/2m_\rho)g_\rho$ (thus yielding the correct isovector form factor for the nucleon), and $f_\varphi = (4M/2m_\varphi)g_\rho$. The ω is introduced arbitrarily, and Sudarshan has set $g_\omega = g_\rho$. However this is in contradiction to recent experiments[3] which predict $g_\omega^2 = (10 \pm 2)g_\rho^2$, assuming vector dominance of the nucleon electromagnetic form factor, so we vary g_ω^2 instead for a best fit to the data. This is explained below; f_ω is varied also.

The π and η pseudoscalar mesons are assumed to be longitudinal components of the A_1 and D fields, obeying partial conservation of axial-vector current. Their explicit interaction Lagrangians are

$$\mathcal{L}_3^{\text{int}} = (4\pi)^{1/2}\bar{\psi}[g_\pi\gamma_5\vec{\tau}\cdot\vec{\pi} + g_\eta\gamma_5\eta]\psi. \tag{2c}$$

We carry out our calculation of nucleon-nucleon scattering using the interaction Lagrangian $\mathcal{L}^{\text{int}} = \mathcal{L}_1^{\text{int}} + \mathcal{L}_2^{\text{int}} + \mathcal{L}_3^{\text{int}}$ [Eqs. (2a)-(2c)] in the following manner: The relativistic one-boson-exchange contributions are calculated and used as a potential in the Bethe-Salpeter (BS) equation. The BS equation is then solved in a Blankenbecler-Sugar (BBS) approximation, as described fully by Thompson.[4] This generates a unitary amplitude from the real (hence nonunitary) Born terms. (For previous work on the Sudarshan model in NN scattering, see Chiang *et al.*[5] and Bryan.[6])

As it turns out, this interaction Lagrangian will not correctly predict known N-N observables when used in this fashion, because the potentials lack sufficient central attraction.[7] The 2π crossed diagram could be added, but it is debatable whether this would suffice since the central repulsion of the ω must be overcome outside 1 F, and g_ω^2 is quite large when adjusted to give the full spin-orbit potential demanded by experiment.[7] Instead, we add in the contributions of the known scalar mesons, the $\epsilon(715)$ with $T, J = 0, 0^+$ and the $\delta(962)$ with $T, J = 1, 0^+$, with the intention of adjusting the coupling constants for a best fit to the data. To some extent, this simulates 2π crossed exchange in addition to scalar meson exchange. The scalar mesons' interaction Lagrangian is taken to be

$$\mathcal{L}_4^{\text{int}} = (4\pi)^{1/2}\bar{\psi}[g_\epsilon\epsilon + g_\delta\vec{\tau}\cdot\vec{\delta}]\psi. \tag{2d}$$

The sum of one-boson-exchange potentials defined by Eqs. (2a)-(2d) is now inserted in the BS (BBS) equation[8,9] and all vector, scalar, and pseudoscalar coupling constants are varied in a search for a best fit to the 0- to 425-MeV p-p and n-p data, as represented by the Arndt-MacGregor-Wright energy-independent phase-shift error matrices at seven energies.[10] In the searches we release f_ρ from the SU(4) condition, but find that it settles to a nearby value. We omit the φ altogether, as its contribution is masked by that of the ω; g_ω and f_ω are both varied, and go to not unreasonable values. The widths of the ρ and ϵ mesons, assumed to be 130 and 400 MeV, respectively, are taken into account in a two-pole approximation.[9] Only the coupling constants of the A_1 and D are not varied, but linked to g_ρ^2 according to Eq. (2a). Searches were carried out on a CDC 6600 computer, and required about 45 min of machine time. The coupling constants ultimately found are listed in Table I. All meson masses were kept at their physical values[11] (as distinct from many other pole models, e.g., Ref. 6, where m_ϵ and m_δ are varied). We shall refer to this model as the extended one-boson-exchange model (EOBE).

The phase parameters predicted by this model are graphed in Fig. 2. The presence of TRV requires a modification of the usual parametrization of the scattering matrix for the coupled states; e.g., the K matrix for the $J = 1$ coupled states is now given by

$$\begin{pmatrix} \langle {}^3S_1|K|{}^3S_1\rangle & \langle {}^3S_1|K|{}^3D_1\rangle \\ \langle {}^3D_1|K|{}^3S_1\rangle & \langle {}^3D_1|K|{}^3D_1\rangle \end{pmatrix} = \begin{pmatrix} K_{00} & K_{02}\exp(2i\lambda) \\ K_{02}\exp(-2i\lambda) & K_{22} \end{pmatrix},$$

where K_{00}, K_{02}, K_{22}, and λ are all real. When λ

Table I. Coupling constants, masses, and widths used in the extended one-boson-exchange model. Coupling constants in parentheses were not independently varied. No masses or widths were varied. The sum of one-boson-exchange terms was multiplied by a Feynman cutoff factor of the form $\Lambda^2/(\Lambda^2 - q^2)$, with $\Lambda = 1271$ MeV. Particle properties taken from Ref. 11.

	$T=0$	$T=1$
$J^P = 0^-$	$g_\eta^2 = 8.78$	$g_\pi^2 = 14.53$
	$m_\eta = 958$ MeV	$m_\pi = 140$ MeV
$J^P = 0^+$	$g_\epsilon^2 = 14.34$	$g_\delta^2 = 1.03$
	$m_\epsilon = 715$ MeV	$m_\delta = 9.62$
	$\Gamma_\epsilon = 400$ MeV	$\Gamma_\delta = 0$
$J^P = 1^-$	$g_\omega^2 = 10.55$	$g_\rho^2 = 0.78$
	$(f/g)_\omega = 0.30$	$(f/g)_\rho = 5.50$
	$m_\omega = 784$ MeV	$m_\rho = 765$ MeV
	$\Gamma_\omega = 0$	$\Gamma_\rho = 130$ MeV
$J^P = 1^+$	$g_D^2 = (0.39)$	$g_A^2 = (1.08)$
	$(f/g)_D = (0.91)$	$(f/g)_A = (1.81)$
	$m_D = 1288$ MeV	$m_A = 1070$ MeV

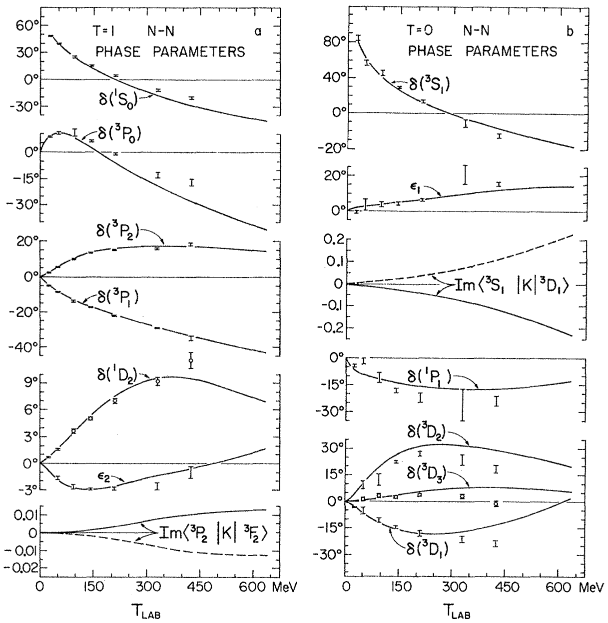

FIG. 2. Phase parameters predicted by the EOBE model. The solid and dashed curves correspond to taking f_A equal to plus and minus $(4M/2m_A)g_A$, respectively. Error bars are due to MacGregor, Arndt, and Wright, Ref. 10.

$=0$, TRV is nonexistent. This parametrization has been suggested by Phillips.[12] K_{00}, K_{02}, K_{20} $(=K_{02})$, and K_{22} constitute a real 2×2 matrix which is parametrized, in turn, according to the usual bar convention of Stapp, Ypsilantis, and Metropolis.[13] The scattering matrices of the coupled states for $J=2, 3, \cdots$ are parametrized analogously. The phase parameters predicted by the EOBE model (Fig. 2) may be seen to agree qualitatively well with the experimental values taken from the Arndt-MacGregor-Wright tables.[10] Note that we show $\mathrm{Im}\langle{}^3S_1|K|{}^3D_1\rangle$ and $\mathrm{Im}\langle{}^3P_2|K|{}^3F_2\rangle$ rather than $\lambda(J=1)$ and $\lambda(J=2)$; λ can be misleadingly large when the real part of the off-diagonal K-matrix element goes through zero, as happens in this model at $T_{\mathrm{lab}}=450$ MeV for $J=2$.

One measure of T-invariance violation is the difference between the polarization P and the asymmetry $\mathcal{A}$. To our knowledge, experiments on $P-\mathcal{A}$ have been carried out only in the p-p system. We show in Fig. 1 the predictions of the EOBE model for $P-\mathcal{A}$ in both the p-p and the n-p systems, at $T_{\mathrm{lab}}=50$, 145, 425, and 635 MeV; p-p measurements at 142 and 635 MeV[2] are also graphed. One may observe that the predicted $(P-\mathcal{A})_{pp}$ is small, even up to 635 MeV, consistent with experiment.[14] For n-p scattering, $P-\mathcal{A}$ is predicted to be small at 50 MeV, consistent with TRV being 1% or less in nuclear physics. However, $(P-\mathcal{A})_{np}$ increases markedly at higher energies and at 635 MeV has a peak value of 0.28 at 140° c.m. (Because of the uncertainty in the EOBE model of the relative sign of the g_A and f_A and also of the g_D and f_D, we have plotted predictions for both possible signs.) A value of $P-\mathcal{A}$ this large should certainly be detectable with present-day experimental techniques.

There are several reasons why the EOBE model predicts much greater T-invariance violation in n-p scattering than in p-p scattering: (1) In n-p scattering T-invariance violation takes place in $J=1$ states, whereas in p-p scattering the nucleons cannot exist in these $J=1$ states because of the Pauli exclusion principle, hence T-invariance violation takes place first in $J=2$ states $(\langle{}^3P_2|K|{}^3F_2\rangle \neq \langle{}^3F_2|K|{}^3P_2\rangle)$. By centrifugal-barrier arguments, the $J=1$ transitions are much stronger than the $J=2$ transitions. (2) The T-invariance violation is due to a very short-ranged force ($m_A=1070$ MeV), and hence shows up much more weakly in the $J=2$ transitions than in $J=1$ transitions. (3) The A_1 pole term goes as $\vec{\tau}_1\cdot\vec{\tau}_2 \times g_A^2$, and hence is three times stronger in the $T=0$ ${}^3S_1 \to {}^3D_1$ transitions than in the $T=1$ ${}^3P_2 \to {}^3F_2$ transitions. [The isoscalar $D(1288)$ pole term is negligible compared to the A_1 pole term.]

Since $P-\mathcal{A}$ of Fig. 1 is predicted by a model with several arbitrary features, one might wonder how likely the predictions are to be true if some of the assumptions turn out to be incorrect. We assert that as long as the TRV mechanism is of very short range, as in A_1 exchange, the angular distributions of $P-\mathcal{A}$ and the rapid falloff with energy will stay the same as in Fig. 1. The angular distributions will stay the same for the following reasons:

$$P-\mathcal{A}=8\,\mathrm{Im}[h(\theta)t(\theta)]I_0^{-1}(\theta),$$

using Phillips's notation,[12] where $h(\theta)$ is one of the five invariant amplitudes, $t(\theta)$ is the TRV amplitude, and $I_0(\theta)$ is the unpolarized differential cross section; $h(\theta)$ and $I_0(\theta)$ are already known from experiment and are correctly reproduced by our model; $t(\theta)$ is not known, but its expansion is

$$t(\theta)=(i/4k)[3\sqrt{2}\,\mathrm{Im}\langle{}^3S_1|T|{}^3D_1\rangle\sin\theta+5(6^{1/2})\,\mathrm{Im}\langle{}^3P_2|T|{}^3F_2\rangle\sin\theta\cos\theta+\cdots].$$

If TRV is very short-ranged,

$$|\mathrm{Im}\langle {}^3S_1|T|{}^3D_1\rangle| \gg |\mathrm{Im}\langle {}^3P_2|T|{}^3F_2\rangle| \gg |\mathrm{Im}\langle {}^3D_3|T|{}^3G_3\rangle|,$$

so that $t(\theta)\propto\sin\theta$ in n-p scattering, and $\propto\sin 2\theta$ in p-p scattering. Thus the θ dependences of t, h, I_0, and hence $P-\mathcal{A}$, are known. Only the overall magnitude of $P-\mathcal{A}$ might be different. But note, e.g., that the peak in the n-p distribution will always occur near 140° c.m. We therefore encourage experimentalists to look in this region.

Since $P-\mathcal{A}$ is sensitive to $h(\theta)$, it is important to reproduce the experimental value of h well; thus, in addition to matching the Arndt-MacGregor phase parameters for $l\leq 6$, we have included the relativistic pion-pole contribution for $l>6$, using the values of g_π^2 and m_π listed in Table I.

Effects which we have not considered but which bear on T-invariance violating predictions above 400 MeV are relativistic corrections to the BS (BBS) equation, and pion production. We believe our current calculations are approximately correct up to 425 MeV. Graphs of $P-\mathcal{A}$ have also been shown at 635 MeV to give a qualitative picture of the expected theoretical predictions.

We would like to thank Professor E. C. G. Sudarshan for several helpful discussions on matters pertaining to this work. We would also like to thank Dr. Judy Binstock for a useful suggestion.

*Supported in part by the U. S. Air Force Office of Scientific Research, Office of Aerospace Research, under Grant No. 69-1817.

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