EXPERIMENTAL INVESTIGATIONS OF P- AND T-VIOLATIONS

D. Hamilton

University of Sussex, Brighton, England, and
CERN, Geneva, Switzerland.

Geneva - September 1969

(Invited paper to be presented at the
International Conference on High-Energy Physics and Nuclear Structure,
Columbia University, New York, 8-12 September, 1969.)

THE FOLLOWING IS A SUMMARY OF THE RESULTS OF THE

ANALYSIS

OF THE DATA OBTAINED FROM THE EXPERIMENTAL

STUDY OF THE EFFECT OF

ON THE RATE OF

REACTION OF THE

SYSTEM WITH THE REACTION OF THE

SYSTEM WITH THE REACTION OF THE

EXPERIMENTAL INVESTIGATIONS OF P- AND T-VIOLATIONS

D. Hamilton

University of Sussex, Brighton, England, and
CERN, Geneva, Switzerland.

1. INTRODUCTION

Experiments to test parity and time violations are difficult. Theoretical estimates of the expected effects are uncertain and it appears that accurate experimental results will be necessary in order to clarify the theoretical position.

The theoretical estimates as have been discussed by Dr. McKellar [1] indicate that the parity mixing of nuclear states could have an amplitude in the range $10^{-6} \lesssim F \lesssim 10^{-7}$. The situation in the case of time reversal is not so clear since the source of a possible time reversal interaction has not been identified. For the case when the interaction is due to a Todd P-even term in the Hamiltonian then the most favourable estimates arise from strong and electromagnetic interactions and have an amplitude of $\lesssim 10^{-3}$, while for a Todd P-odd interaction the amplitude is probably not greater than $\sim 10^{-9}$ times the regular interaction.

2. EXPERIMENTAL TESTS OF PARITY VIOLATION

The basis of these tests was laid by Wilkinson [2]. One may search for a transition which could only occur if parity mixing of nuclear states occurred. The intensity of the transition will be of the order F^2 , i.e. $\sim 10^{-12}$ to 10^{-14} compared with the intensity that a similar allowed transition would have. The alternative and more direct test is to establish the presence of a pseudoscalar term. This test falls into two categories; a measurement of a forward-backward asymmetry in the radiation emitted by polarized nuclei, or the detection of the circular polarization of radiation from a

random assembly of nuclei. The extent of these pseudoscalar interactions is proportional to the amplitude of the parity admixture, F , since they arise from an interference between the normal electromagnetic decay and that occurring as a result of the parity mixing of the nuclear states. Thus one is searching for an effect which may be as small as one part in 10^6 compared to the regular process.

Let us now consider in some detail the present position in these different types of experiment.

2.1 Parity Violating Transition

The most sensitive conditions for observing a parity violating transition occur in the α -decay of the 8.88 MeV 2^- state in ^{16}O to the 0^+ ground state of ^{12}C . Normal α -decay is absolutely forbidden. A good resolution experiment is necessary in order to identify the weak parity violating transition in the tails of neighbouring intense regular transitions and also to distinguish the possibility of decay of the 2^- state by an allowed higher order process. One must also be confident that the decay scheme could not allow a weak normal transition of comparable energy.

The 8.88 MeV 2^- state is populated following the β^- decay of the 2^- ground state of ^{16}N , and this ensures that the decay to the even parity states in ^{16}O is relatively small. From the systematics of 2^+ states one can estimate that expected α -decay width of an

Fig. 1 a) The β^- decay of ^{16}N to levels in ^{16}O which may subsequently decay by α -emission to ^{12}C .

b) The decay of the neutron capture state in ^{114}Cd to the ground and first excited state. The majority of decays occur to higher energy levels.

8.88 MeV 2^+ state is about 6.7 keV. Measurements by Boyd et al. [3] indicate that the α -decay width of the equivalent 2^- state is less than 1.1×10^{-12} keV. It can be concluded that $|F| \gtrsim 4 \times 10^{-6}$.

2.2 Gamma-Ray Asymmetry from Polarized Nuclei

The measurement of pseudoscalar quantities which can be associated with parity violation has been the most popular way of trying to establish the strength of the parity violating interaction.

The first measurement which reported a non negative result was carried out by Abov et al. [4]. They measured an asymmetry in neutron capture γ -rays from ^{114}Cd with respect to the neutron polarization. The transitions in the 9 MeV region were selected since the M1 ground state transition from the 1^- level at 9.05 MeV might be expected to contain an irregular E1 admixture. These measurements have been repeated by Warming et al. [5] and also by Abov et al. [6]. The most recent measurements by Warming [7] used a Ge-detector and with the improved resolution it was possible to separate easily the 9.05 MeV and 8.48 MeV transitions. Since it is not expected that the E2 + M1 8.48 MeV transition contains any significant parity admixture she corrected previous data for the contribution of this transition in the 9.05 MeV region. The results are given in Table 1.

The original Abov data indicate a very strong asymmetry; there is less than 0.1% probability that it is zero. However both data by Warming are consistent with a small or zero asymmetry. Theoretical values have poor accuracy and most include zero as a possible answer.

An alternative method of selecting nuclei with a particular polarization is to determine the direction of β -decay of these nuclei.

Table 1

Gamma-ray asymmetry of the 9.05 MeV M1 Transition emitted by polarized ^{114}Cd nuclei

Measured asymmetry	Correction factor ^{a)}	Corrected asymmetry	Reference
-3.7 ± 0.9	40	-6.1 ± 1.5	Abov et al. [4]
-2.5 ± 2.2	0	-2.5 ± 2.2	Warming et al. [5]
-3.5 ± 1.2	20	-4.4 ± 1.5	Abov et al. [6]
$-0.6 \pm 1.7^{\text{b)}$	5	-0.6 ± 1.8	Warming [7]

a) The correction factor represents the contribution of the unresolved 8.48 MeV γ -ray in the detected spectrum. This is an M1 + E2 transition and may not be expected to show an asymmetry.

b) Measured using a Ge-detector, all other results were obtained using NaI-detectors.

The asymmetry of a subsequent γ -ray can then be measured with respect to the β -direction.

An experiment of this type was first carried out by Boehm and Hauser [8] who search for the presence of an odd Legendre polynomial term in a β - γ correlation in which the β -transition was allowed. They used a conventional correlation technique with a moving detector and their accuracy was limited. A novel method capable of an inherently high degree of accuracy is being used by Baker and Hamilton [9]. It is based on a symmetric four detector arrangement which can simultaneously measure the forward ($\theta = 0$) and backward ($\theta = \pi$) β - γ correlations.

Uncertainties in detector efficiency and solid angle corrections are removed by interchanging one pair of detectors since by combining the results of both measurements these factors cancel. In addition this combination can be arranged such that the measurements give the value $1 + 8A$ where A is the asymmetry. A detailed analysis also shows that no correction is required for accidental coincidences; higher order terms are negligible if $A \lesssim 10^{-3}$. Electronic stability is largely achieved by having one master coincidence circuit for the four possible coincidence combinations and using routing units to sort these combinations. The more important effects due to electronic drifts can be removed by choosing a short counting period between each rotation of the γ -detectors and using data sampling techniques.

Fig. 2 A schematic representation of the detector system is shown together with an expression indicating how the coincidence counts may be combined. Also shown is the decay scheme of ^{203}Hg .

They chose to measure the β - γ correlation in ^{203}Hg for which they confirmed that the coefficient of the even Legendre polynomial, P_2 , was zero, i.e. the normal β - γ correlation is isotropic. It is a particularly suitable case since the 279 keV $d_{3/2}$ state in ^{203}Tl is fed 100% by the β -decay. This state then decays by an E2-M1 transition to the $s_{1/2}$ ground state. The M1 component is thus ℓ -forbidden which results in a relative enhancement of a parity violating $\tilde{\text{E}}1$ admixture. The decay scheme is also favourable since the energies of the β - and γ -transitions allow discrimination against possible sources of error such as bremsstrahlung and multiple scattering.

A similar method has been used by Bock [10] who used a correlation angle of 45° for which any contribution from a P_2 term will be zero. The results are given in Table 2.

2.3 Gamma-Ray Circular Polarization

The most popular method of searching for parity violation is to determine the degree of helicity of γ -rays emitted by a random assembly of nuclei. At first sight it is an attractive experiment since no coincidence or correlation measurements are necessary. However, it suffers from the serious disadvantage that the only method of analysing circular polarization available to low-energy nuclear physics is by Compton scattering from polarized electrons. In magnetized iron only 7% of the electrons are polarized and the polarization efficiency of an analyser is seldom more than a few per cent. This poor analysing power of the detection system to some extent may be compensated for by choosing a suitable transition.

The 482 keV E2 + M1 transition in ^{181}Ta has been studied most often. The M1 component is hindered by the selection rules associated with the Nilsson asymptotic quantum numbers and has a hindrance of $\sim 3 \times 10^6$, while the possible $\tilde{\text{E}}1$ admixture is unhindered. Thus the circular polarization, which is proportional to the $\langle ||\tilde{\text{E}}1|| \rangle : \langle ||\text{M1}|| \rangle$ matrix element ratio is large. This ratio is

Table 2
Gamma-ray asymmetries in β - γ correlations

Nucleus	Asymmetry $\times 10^{-4}$	F	Reference
^{133}Xe	15 ± 15	$\leq 7.5 \times 10^{-6}$	Boehm and Hauser [8]
^{203}Hg	1.5 ± 0.9	$\sim 10^{-6}$	Baker and Hamilton [9]
^{203}Hg	≤ 10	$\leq 10^{-5}$	Bock [10]

commonly written as the product FR where R contains the nuclear structure information. In the case of ^{181}Ta , special circumstances and certain assumptions make it possible to evaluate R with some confidence [11] and one obtains for the circular polarization

$$P_{\gamma} = - (1.6^{+1.8}_{-0.9}) \times 10^2 F .$$

Thus one may expect a circular polarization of $P_{\gamma} \sim -10^{-4}$, and because of the low efficiency of the analyser the effect searched for is no larger than one part in 10^6 .

The most serious limitation in the past has been that set by pulse counting rate. It is difficult to achieve much more than several MHz without pulse pile-up limitations. This requires the experiment to be run for many months in order to achieve the required statistical accuracy and to carry out the various control experiments. A very significant improvement in experimental technique by Lobashov et al. [12] removes this limitation. They use an integral counting method and measure the change in the scintillator light output when the sensitivity of the circular polarimeter is reversed. The source strength may be increased by several orders of magnitude so that an effective counting rate of GHz may be used, which significantly shortens the time required to obtain adequate statistical accuracy. The method is now being used in other laboratories. The more recent results obtained for circular polarization measurements are given in Table 3.

Until recently only the result obtained in 1967 by Lobashov et al. [12] excluded a zero effect with any great confidence. It is also unlikely that an effect as small as that reported by Lobashov could be seen using a conventional pulse-counting system. However, using just such a system but with an array of detectors, Bodendstedt et al. [15] have obtained a result which is about five times larger than that of Lobashov and differs from it by more than three standard deviations. The preliminary results of Vanderleeden and Boehm [17] and Bock and Jentschke [18] support Lobashov. Indeed the result of Bock and Jentschke, which contains no correction for bremsstrahlung, indicates that P_{γ} may be much smaller since they expect their bremsstrahlung correction to be comparable to the observed effect. It should be stressed that some of the data in Table 3 are preliminary and very recent.

The integral counting technique offers the only way so far of measuring such small effects in a comparatively short experimental time. It does suffer from the disadvantage that energy discrimination is impossible and one must rely on lead filters to remove unwanted low-energy radiation such as strongly polarized bremsstrahlung.

Table 3

The circular polarization of γ -rays emitted in nuclear transitions by a random assembly of nuclei. The results marked thus * should only be considered as preliminary values.

Nucleus	Method		Polarization $\times 10^{-5}$	Theory ^{a)} $\times 10^{-5}$	Ref.
	Magnet	Counting			
¹⁸¹ Ta	Fwd. sc	integral	-0.6 ± 0.1	-2 ± 1	Lobashov et al. [12]
	Trans.	pulse	-1.0 ± 4.0		Boehm and Kankleit [13]
	Fwd. sc.	pulse	-2.0 ± 4.0		Bock [10]
	Trans.	pulse	-9.0 ± 6.0		Cruse and Hamilton [14]
	Back sc.	pulse	-3.2 ± 0.8		Bodenstedt et al. [15]
	Trans.	integral	* -1.3 ± 0.7		Diehl et al. [16]
	Fwd. sc.	integral	* -0.38 ± 0.13		Vanderleeden and Boehm [17]
	Fwd. sc.	integral	* $-0.6 \pm 0.2^b)$		Bock and Jentschke [18]
¹⁷⁵ Lu 396 keV	Fwd. sc.	integral	$+4 \pm 1$	$\pm(3 \pm 2)$	Lobashov et al [19]
	343 keV	Trans.	pulse	$+2 \pm 3$	-1.0 ± 0.5 Boehm and Kankleit [13]
²⁰³ Tl	Trans.	pulse	-2 ± 3	-3 ± 1	Boehm and Kankleit [13]
	-	pulse	$-1.3 \pm 0.8^c)$		Baker and Hamilton [9]

- a) The theoretical values are those of McKellar [20] and are based on the conventional Cabibbo model.
b) Obtained using only 1 mm of lead as filter and uncorrected for bremsstrahlung, which is expected to be comparable to the size of the measured effect.
c) Deduced from β - γ anisotropy, cf. Table 2.

2.4 Mössbauer Experiments Sensitive to Parity Mixing

The remaining method which has been used in low-energy nuclear physics has searched for small differences in the intensities of the hyperfine components of a Mössbauer spectrum. The intensities of the $\Delta m = \pm 1$ components of an M1 transition with respect to the direction of nuclear polarization will be unequal if an $\tilde{E}1$ admixture is present.

No recent results have been reported and the most accurate value is that of Kankleit [21], who showed that the $+1/2 \rightarrow -1/2$ and $-1/2 \rightarrow +1/2$ components in the 14.4 keV transition in ⁵⁷Fe were equal to at least one part in 10^5 .

2.5 High-Energy Tests

There have been very few specific high-energy experiments to test parity violation. Several were made about ten years ago and in addition to possible instrumental limitations the most serious difficulty was lack of statistics.

Garwin et al. [22] and Heer et al. [23] searched for pseudo-scalar terms associated with pion decay. The lowest limit which it was possible to set was $F \leq 10^{-3}$. Jones et al. [24] attempted to measure the longitudinal polarization of a 350 MeV neutron beam produced by the interaction of unpolarized protons with an unpolarized target. Again only a limit, $|F| \leq 2 \times 10^{-3}$, could be set.

As we shall see when discussing time-reversal experiments, the accuracy has been improved by about an order of magnitude, but low-energy experiments remain the most accurate way of obtaining evidence for parity violation.

2.6 Future Experiments

There still remains confusion about the extent to which parity is violated in strong and electromagnetic interaction processes. The range of results which are available serve to show how difficult these experiments are, rather than providing a quantitative estimate on which theoretical evaluations may be based. Thus although the latest results for ^{181}Ta indicate that the extent of parity violation may be as much as an order of magnitude less than predictions based on the conventional Cabibbo model, it is unlikely that the nuclear model aspects of the problem could be evaluated with sufficient accuracy to allow a decision to be made about the terms present in the parity violating potential.

It is thus important to have accurate experimental results for less complex systems. Henley [25] has proposed several cases in light nuclei where the nuclear aspects of the problem appear to be well understood and one may also see the effects of the isobaric spin selection rule. An alternative approach is to study reactions of the type

$$n + p \rightarrow d + \gamma .$$

Using polarized neutrons one could search for an asymmetry in the γ -ray emission. However, since there is no large retardation of the normal radiative process, as may occur in complex nuclei, the effect is not expected [26] to be bigger than $\sim 10^{-7}$ and may be as small as 10^{-8} . Experiments on the reaction $^2\text{H}(n,\gamma)$ are in progress but as yet no results of a statistical significance have been reported.

3. EXPERIMENTAL TESTS OF T-VIOLATION

In the same year in which two papers, presented as the Paris Conference (1964), reported evidence for P-violation, Christenson et al. [27] published their results showing CP-violation. And while the first parity results now appear to have been an order of magnitude too large, Christenson's results are well established.

However the complementary problem of determining the extent of T-violation has made little progress over this period and the accuracy of any experiment is not more than $\sim 0.1\%$.

This large difference of 10^3 in the limit of accuracy that may be obtained between P- and T-violation experiments largely represents the difference in the degree of difficulty between the two types of measurement. Time reversal is insensitive to selection rules and, since both angular and linear momentum change sign under T-reversal, one requires experiments capable of measuring quantities of the type^{*)}

$$\vec{\sigma} \cdot \vec{p}(1) \times \vec{p}(2) .$$

This correlation between two momentum vectors in the plane perpendicular to the polarization axis of the interaction system should be zero for T-invariance. Such a quantity is obviously several orders of magnitude more difficult to measure than say a γ -ray asymmetry from a polarized nucleus, i.e. $\vec{\sigma} \cdot \vec{p}$, which will test P-violation.

Although it is generally accepted that CP is violated, and consequently T, there is no experimental evidence or good theoretical reasons which allow the source of the violation to be identified. This allows the experimentalist a wide range of tests.

The present experimental position will be summarized from the viewpoint of the interaction which is tested, or the type of test carried out.

3.1 Weak Interaction Tests

Time invariance implies that there should be no phase difference between the V and A interactions. The electron-neutrino angular correlation following β -decay of a polarized nucleus, i.e. $\vec{\sigma}(N) \cdot \vec{p}(e) \times \vec{p}(\nu)$, will be sensitive to this interference. Two accurate experiments have been carried out: Erozalimsky et al. [30] measured the asymmetry in the electron-proton correlation on reversing the spin of the neutron, and Calaprice et al. [31] used an atomic beam experiment to polarize ^{19}N (ground state spin $1/2$) from which they measured the positron - ^{19}F correlation. The results of these measurements are given in Table 4.

Time invariance implies that θ is 0° or 180° and the experiments indicate that T-violation is less than $\sim 1\%$. Final state electromagnetic interactions are negligible compared with the present

---

*) Comprehensive surveys of these types of measurements are given in Refs. [28] and [29].

Table 4
Weak interaction tests of T-invariance

Decay process	Phase shift θ	Reference
$n \rightarrow p + e^- + \bar{\nu}$	$178.7^\circ \pm 1.3^\circ$	Erozolimsky et al. [30]
$^{19}\text{Ne} \rightarrow ^{19}\text{F} + e^+ + \nu$	$180.2^\circ \pm 1.6^\circ$	Calaprice et al. [31]
$K^0 \rightarrow \pi + \mu + \nu$	$180.5^\circ \pm 2.2^\circ$	Helland et al. [33]
$\Lambda^0 \rightarrow \pi^- + p^a)$	$9.0^\circ \pm 5.5^\circ$	Overseth and Roth [34]
	$9.6^\circ \pm 5.3^\circ$	Anderson et al. [35]

a) Final state interactions are important and give a phase shift of $6.4^\circ \pm 1.7^\circ$, i.e. the result is consistent with T-invariance.

accuracy*). It has also been pointed out by Marchioro et al. [32] that if second class axial currents are a source of T-violation then one might expect null results for n and ^{19}Ne decays.

The other tests of this type are high-energy experiments and are less accurate. The correlation $\vec{\sigma}_\mu \cdot \vec{p}_\pi \times \vec{p}_\mu$ has been studied in the decay $K \rightarrow \pi + \mu + \nu$. The correlations give the value $\text{Im } \xi$, where ξ is a ratio of form factors describing the decay. From a knowledge of $\text{Re } \xi$ one can construct $\theta = \arg \xi$. There exists uncertainty at different stages of the analysis but Helland et al. [33] have analysed the K^0 decay and obtain $\theta = 180.5^\circ \pm 2.2^\circ$. Again final state interactions are negligible.

In the decay $\Lambda^0 \rightarrow \pi^- + p$ there can be no term of the type $\vec{\sigma}_p \cdot \vec{\sigma}_\Lambda \times \vec{p}_p$ unless there is a phase difference between the s- and p-wave amplitudes. Experimentally the average value of the correlation is $\theta = 9.3^\circ \pm 3.8^\circ$ [34, 35]. However, final state interactions are important and the π -N scattering phase shift gives $\theta = 6.7^\circ \pm 1.7^\circ$.

3.2 Electromagnetic Interaction Tests

A Todd term will allow a phase difference, η , between components of a mixed cascade which, for T-invariance, should be 0° or 180° . If in addition a Podd term is present multipoles of opposite parity will have a phase difference of $\pi/2 \pm \eta$ and the phase difference

---

*) It should also be added that strong and electromagnetic interactions are also present in the decays, and if a non-zero effect was found then it would be necessary to locate its source.

between similar parity multipoles is a second order effect, $\lesssim 10^{-9}$, and negligible. Jacobsohn and Henley [28] and Boehm [29] have set out the principles on which these tests can be made.

The tests are often low-energy experiments using radioactive sources and, in principle, it should be possible to obtain good statistical accuracy. The correlation $\vec{\sigma} \cdot \vec{k}_1 \times \vec{k}_2$ is measured using an initially polarized nucleus which decays by a γ - γ cascade. The first member is mixed and the two components should have approximately equal amplitudes since the magnitude of the interference term, $\sin \eta$, in the correlation is proportional to the multipole mixing ratio.

The initial polarization may be provided by a β -decay and Garrell et al. [36] examined two β - γ - γ triple correlations in ^{56}Mn . They have opposite signs for δ . By combining the two results, inherent asymmetries in the system should be removed. They found that the over-all difference in phase between the two transitions was $(4 \pm 26) \times 10^{-3}$. The individual results are listed in Table 5 together with the result for a similar correlation in ^{106}Pd [37].

An alternative method of polarizing the initial state is by the capture of polarized neutrons. The lowest limit of a phase difference so far reported is by Eichler [38].

The Mössbauer effect also provides a sensitive method of testing for T_{odd} terms. These experiments are sophisticated in concept

Table 5
Angular correlation tests of T-invariance in the electromagnetic interaction. The measured phase difference between the E2 and M1 components in the mixed cascade is denoted by η .

Experiment	Source	$\eta \times 10^{-3}$	Reference
Mössbauer absorption	^{99}Ru	1.1 ± 1.7 a)	Kistner [40]
Mössbauer emission	^{193}Ir	1.1 ± 3.8 a)	Atac et al. [42]
β - γ (E2 + M1) - γ (E2) correlation	^{56}Mn	-26 ± 14 ($\delta = -0.28$) -45 ± 27 ($\delta = 0.18$)	Garrell [36]
" "	^{106}Pd	4 ± 18	Perkins and Ritter [37]
Pol. n capture γ (E2 + M1) - γ	^{36}Cl	0.8 ± 2.3	Eichler [38]
	^{49}Ti	17 ± 25	Kajfoz et al. [39]

a) After correction for a phase shift introduced by the internal conversion process, these results are $(0 \pm 1.7) \times 10^{-3}$ [^{99}Ru] and $(0.2 \pm 3.8) \times 10^{-3}$ [^{193}Ir].

and complex in operation. The experiment by Kistner [40] seeks to measure an asymmetry in linearly polarized Mössbauer components following their resonant absorption by polarized nuclei. He used a ^{99}Ru source and chose the $\frac{5}{2} \rightarrow \frac{3}{2}$ and $-\frac{5}{2} \rightarrow -\frac{3}{2}$ components. The interaction of the radiation with a magnetized absorber produces linearly polarized radiation and a second similar absorber may be used to analyse the change in intensities of the two selected components when the field direction in this second absorber is reversed. The experiment is complicated by the fact that the analysing absorber, and its field, were placed at an angle with respect to the photon direction in order to make the P_{odd} term maximum. This in turn caused the radiation resonantly emitted by the analysing absorber have a different polarization to the incident radiation so that the subsequent behaviour of the resonant radiation is different. Thus the polarization of the radiation changes as it passes through this absorber - Faraday rotation. The accurate assessment of this Faraday rotation [41] is necessary for the analysis of the asymmetry.

A similar experiment has been carried out by Atac et al. [42] using the 73 keV transition in ^{193}Ir . In their case they were able to remove the Faraday rotation effect by maintaining the analysing field perpendicular to the photon direction.

An important limitation to the sensitivity of these experiments arises as a result of the interaction of the radiation field with the atomic electrons by the internal conversion process [43]. There exists a phase difference between the internal conversion currents for the M1 and E2 processes which is not associated with T-violation and is important for these accurate Mössbauer experiments. The corrections have been calculated [44] and the corrected result for ^{193}Ir is

$$\eta = (0.2 \pm 3.8) \times 10^{-3}$$

and like Kistner's result, for which the correction is less certain because of Faraday rotation, does not show any evidence of T-violation.

The high-energy tests of the electromagnetic interaction are still at a preliminary stage. The detailed balance test involving the emission or absorption of a photon in the reaction

$$\gamma + d \leftrightarrow n + p$$

has been studied using 300 MeV γ -ray and the differential cross-section was measured by Anderson et al. [45]. The reverse reaction has been measured by Friedberg et al. [49] using neutrons in the 200 to 600 MeV energy range but the final data analysis has not yet been published.

An alternative method is to observe the inelastic scattering of electrons by polarized protons. Again the quantity $\vec{\sigma}(p) \cdot \vec{p}(e_1) \times \vec{p}(e_2)$ can be constructed and virtual photon emission serves as the T-violation test. The analysis of the data is very dependent on assumption about the reaction and the accuracy obtained by Chen et al. [50] was only about 5%.

3.3 Detailed Balance

Besides the preceding detailed balance experiments, other reactions, as discussed by Henley and Jacobsohn [28], may be used in sensitive tests. However, some care must be taken since detailed balance does not necessarily imply T-invariance. This is most easily seen for reactions which are described by the Born approximation, since in this case the transition matrix elements are Hermitian.

Although it appears that the best tests involve reactions which proceed through a many channel compound nucleus, uncertainties in nuclear reaction theory limit this method. The few very accurate experiments that have been carried out are limited to direct interactions for which the T_{odd} part of the interaction potential could be identified.

The experimental situation is simplest when the first excited state is relatively high as in light nuclei. In addition the analysis is greatly simplified if the number of spin channels available for the reaction is small. This may be achieved by having low spin values for the nuclei involved in the reaction and choosing suitable reaction angles.

The results of recent accurate experiments are given in Table 6.

In the case of the $^{24}\text{Mg}(\alpha;p)^{25}\text{Mg}$ reaction the angles were 30° and 120° with respect to the beam and many spin channels were possible, while only one spin channel was possible for the $^{24}\text{Mg}(\alpha;p)^{27}\text{Al}$ reaction since the particles were detected in the backward direction.

Table 6
Detailed balance tests of T-violation. The ratio of the T_{odd} to T_{even} matrix elements is denoted by A.

Reaction	$A \times 10^{-3}$	Reference
$^{24}\text{Mg} + d \leftrightarrow ^{25}\text{Mg} + p$	$\lesssim 3$	Weitkamp et al. [46]
$^{24}\text{Mg} + \alpha \leftrightarrow ^{27}\text{Al} + p$	$\lesssim 3$	Von Witsch et al. [47]
$^{16}\text{O} + d \leftrightarrow ^{14}\text{N} + \alpha$	$\lesssim 3$	Thornton et al. [48]

4. TESTS FOR P_{odd} T_{odd} TERMS

The simultaneous violation of P and T may be expected to give rise to an effect having a magnitude equal to the product of the separate P- and T-violating processes, i.e. not greater than $\sim 10^{-9}$. And, although one may choose a γ -ray transition in which selection rules enhance the P-violating component, the angular correlation tests as outlined by Boehm [29] appear beyond the range of presently available techniques.

However another aspect of the problem shows that P- and T-invariance of the electromagnetic field implies that a non-degenerate state cannot have odd electric or even magnetic multipoles. The most suitable system in which one might search for these forbidden multipoles would be a neutral atom of spin $1/2$. And the simplest of these is the neutron.

Several very accurate experiments [51,52] have searched for the electric dipole moment of the neutron. They owe their high degree of accuracy to the precision with which small changes of frequency in the RF region can be measured. A combination of electric and magnetic fields can be set up in an RF resonance spectrometer and the frequency set to the precessional frequency of the neutrons. On reversing the electric field the presence of an electric dipole moment would be observed as a shift in magnetic resonance frequency. The most recent measurements by Baird et al. [53] set the limit on the electric dipole moment of the neutron at

$$|\mu_e| < 5 \times 10^{-23} \text{ e cm}.$$

This value is about an order of magnitude less than the upper limit of $\mu_e \lesssim 6 \times 10^{-22} \text{ e cm}$ for an electromagnetic violation of CP invariance [54]. However it is still larger than the range of values expected from a milliweak theory, $10^{-24} \text{ e cm} \lesssim \mu_e \lesssim 10^{-23} \text{ e cm}$.

In conclusion, the evidence for P-violation now appears to be well-established following the most recent experiments and the results are consistent with the current-current interaction of the non-leptonic part of the weak interaction. The experimental accuracy for the T-violation experiments is barely adequate to test the origin of T-violation, although only a small improvement would bring the accuracy limit to within the predictions based on T-violation stemming from the electromagnetic interaction of the hadrons.

REFERENCES

1. B.H.J. McKellar, preceding contribution.
2. D.H. Wilkinson, Phys.Rev. 109, 1603 (1958).
3. D.P. Boyd, P.F. Donovan, B. Marsh, D.E. Alburger, D.H. Wilkinson, P. Assimakopoulos and E. Beardsworth, Bull.Am.Phys.Soc. 13, 1424 (1968).
4. Y.G. Abov, P.A. Krupchitsky and Y.A. Oratovsky, Phys.Letters 12, 25 (1964).
5. E. Warming, F. Stecher-Rasmussen, W. Ratynski and J. Kopecky, Phys.Letters 25B, 200 (1967).
6. Y.G. Abov, P.A. Krupchitsky, M.I. Bulgakov, O.N. Yermakov and I.L. Karpikhin, Phys.Letters 27B, 16 (1968).
7. E. Warming, Phys.Letters 29B, 564 (1969).
8. F. Boehm and U. Hauser, Nucl.Phys. 14, 615 (1959).
9. K.D. Baker and W.D. Hamilton, to be published.
10. P. Bock, Thesis, Karlsruhe (1969).
11. S. Whalborn, Phys.Rev. 138, B530 (1965).
12. V.M. Lobashov, V.A. Nazarenko, L.F. Saenko and L.M. Smotritskii, JETP Letters 5, 59 (1967).
13. F. Boehm and E. Kankleit, Nucl.Phys. A109, 457 (1968).
14. D.W. Cruse and W.D. Hamilton, Nucl.Phys. A125, 241 (1969).
15. E. Bodenstedt, L. Ley, H.O. Schlenz and U. Wehmann, Phys. Letters 29B, 165 (1969).
16. H. Diehl, G. Hopfensitz, E. Kankleit and E. Kuphal, contributed paper to this conference.
17. J.C. Vanderleeden and F. Boehm, contributed paper to this conference.
18. P. Bock and H. Jentschke, Private communication, September 1969.
19. V.M. Lobashov, V.A. Nazarenko, L.F. Saenko and L.M. Smotritskii, JETP Letters 3, 173 (1966).
20. B.H.J. McKellar, Phys.Rev.Letters 21, 1822 (1968).
21. E. Kankleit, Comptes Rendus du Congrès Int. de Phys.Nucl., Paris 1964, paper 5/C293.
22. R.L. Garwin, G. Gidal, L.M. Lederman and M. Winrich, Phys. Rev. 108, 1589 (1957).
23. E. Heer, A. Roberts and J. Tinlot, Phys.Rev. 111, 645 (1958).
24. D.P. Jones, P.G. Murphy and P.L. O'Neill, Proc.Phys.Soc. 72, 429 (1958).
25. E.M. Henley, Phys.Letters 28B, 1 (1968).
26. G.S. Danilov, Phys.Letters 18, 40 (1965).
27. J.H. Christenson, J.W. Cronin, V.L. Fitch and R. Turlay, Phys. Rev.Letters 13, 138 (1964).
28. E.M. Henley and B.A. Jacobsohn, Phys.Rev. 113, 225 (1959).
29. F. Boehm in Hyperfine Structure and Nuclear Radiations, North-Holland, Amsterdam (1968).
30. B.G. Erokolimsky, L.N. Bondarenko, Y.A. Mostovoy, B.A. Obinyakov, V.P. Zacharova and V.A. Titov, Phys.Letters 27B, 557 (1968).

31. F.P. Calaprice, E.D. Commins, H.M. Gibbs, G.L. Wick and D.A. Dobson, UCRL-18647 (1969) and to be published in Phys.Rev.
32. C. Marchioro, A. Prosperetti and A. Pugliese, preprint (1969).
33. J.A. Helland, M.J. Longo and K.K. Young, Phys.Rev.Letters 21, 257 (1968).
34. O.E. Overseth and R.F. Roth, Phys.Rev.Letters 19, 391 (1967).
35. T. Anderson, J.K. Bienlein, W.E. Cleland, G. Conforto, G.H. Eaton, H.J. Gerber, M. Reinharz, M. Veltman, A. Gautschi, E. Heer, J.F. Renevey, C. Revillard and G. von Dardel, Proc. 14th Int.Conf. on High-Energy Physics, Vienna (1968).
36. M.H. Garrell, Thesis, University of Illinois (1966).
37. R.B. Perkins and E.T. Ritter, Phys.Rev. 174, 1426 (1968).
38. J. Eichler, Nucl.Phys. A120, 535 (1968).
39. J. Kajfosz, J. Kopecky and J. Honzatkó, Nucl.Phys. A120, 225 (1968).
40. O.C. Kistner, Phys.Rev.Letters 19, 872 (1967).
41. M. Blume and O.C. Kistner, Phys.Rev. 171, 417 (1968).
42. M. Atac, B. Chrisman, P. Debrunner and H. Frauenfelder, Phys. Rev.Letters 20, 691 (1968).
43. E.M. Henley and B.A. Jacobsohn, Phys.Rev.Letters 16, 706 (1966).
44. J.P. Hannon and G.T. Trammell, Phys.Rev.Letters 21, 726 (1968).
45. R.L. Anderson, R. Prepost and B.H. Wiick, Phys.Rev.Letters 22, 651 (1969).
46. W.G. Weitkamp, D.W. Storm, D.C. Shreve, W.J. Braithwaite and D. Bodansky, Phys.Rev. 165, 1233 (1968).
47. W. von Witsch, A. Richter and P. von Brentano, Phys.Rev. 169, 923 (1968).
48. S.T. Thornton, C.M. Jones, J.K. Blair, M.D. Mancusi and H.B. Willard, Phys.Rev.Letters 21, 447 (1968).
49. C.E. Friedberg, D.F. Bartlett, K. Goulianos, I.S. Hammerman and D.P. Hutchinson, Bull.Am.Phys.Soc. 14, 76 (1969).
50. J.R. Chen, J. Sanderson, J.A. Appel, G. Gladding, M. Goiten, K. Hanson, D.C. Imrie, T. Kirk, R. Madaras, R.V. Pound, L. Price, R. Wilson and C. Zajde, Phys.Rev.Letters 21, 1279 (1968).
51. C.G. Shull and R. Nathans, Phys.Rev.Letters 19, 384 (1967).
52. W.B. Dress, J.K. Baird, P.D. Miller and N.F. Ramsey, Phys. Rev. 170, 1200 (1968).
53. J.K. Baird, P.D. Miller, W.B. Dress and N.F. Ramsey, Phys.Rev. 179, 1285 (1969).
54. G. Barton and E.D. White, Preprint (1969).