Simulated $T$-Violation Effects
in Elastic Electron-Proton Scattering.

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Summary. — An algebraic derivation is given of simulated $T$ violations in an elastic electromagnetic process. The theoretical differential cross-section $d\sigma$ for high-energy elastic electron-proton scattering is shown to contain certain spin-momentum correlations $A_{s.m.} s \cdot p_1 \times p_2$ which seem to violate time reversal $T$. Since the primary electromagnetic-interaction Hamiltonian is assumed to be $C$ and $T$ invariant, the appearance of such triple scalar products in $d\sigma$ implies a simulated violation in $T$. The present computation shows that these simulated violations can occur even in elastic processes, where they specifically arise from the interference between the real second-order amplitude and the imaginary fourth-order amplitude. Our calculation includes both crossed and uncrossed Feynman graphs to fourth order in $\epsilon$. There is no cancellation of the relevant terms to order $\epsilon^6$. The cross-section for simulated effects, for the subamplitude $M_0$, is found to be $d\sigma/d\Omega_3 \approx 0.25 \cdot 10^{-36}$ cm$^2$/sr at a laboratory angle $\theta = 20^\circ$, $-q^2 = 2.28$ (GeV/c)$^2$ and an incident electron energy $E_2 = 5$ GeV/c. Symmetry arguments concerning triple scalar products are based on the validity of the $CPT$ theorem.

1. — Introduction.

The purpose of this article is to present an algebraic derivation of simulated $T$ violations in an elastic electromagnetic process. The simulated effects can occur even if the primary Hamiltonian $H_\gamma$ is invariant under charge conjugation $C$ and time reversal $T$. 
Simulated effects have been discussed previously by Cabibbo and Veltman (1), Karplus, Leonardi and Strocchi (2) and others (3). Callan and Treiman (4) and the present author (5) have shown that simulated T violations can occur in processes where the interaction Hamiltonian is weak (neutron beta decay and high-energy neutrino scattering). The present paper differs from previous works on two major points:

a) The article gives higher-order (2\alpha) corrections of simulated effects; by comparison, the calculations in ref. (3,4) are carried out to lowest order in \alpha.

b) The paper contains, as far as we know, the first algebraic calculation of simulated effects for an elastic electromagnetic interaction. The computations in ref. (4,5), on the other hand, deal with inelastic interactions, whose primary Hamiltonian is weak.

Information about the invariance of a particular interaction Hamiltonian \( H_{int} \) can be obtained from the differential cross-section \( d\sigma \) for a specific scattering process. Invariance of \( H_{int} \) under time reversal \( T \) forbids the appearance in \( d\sigma \) of spin-momentum correlations such as \( A_{e.m.} \cdot \mathbf{s} \cdot \mathbf{p}_1 \times \mathbf{p}_2 \), provided the interaction effects are described by an \( S \)-matrix to lowest order in \( H_{int} \) (\( \mathbf{s} \) is the polarization vector, \( A_{e.m.} \) the asymmetry parameter and \( \mathbf{p}_1, \mathbf{p}_2 \) are linear momenta.)

It is important to realize that expressions like «T invariance» or «T non-invariance» refer to the primary interaction, and not to final-state or higher-order effects (secondary interactions). The presence of secondary effects alters the above symmetry arguments in as much as triple scalar products may now appear in the theoretical cross-section, even though the primary interaction Hamiltonian is \( T \) invariant. Triple scalar products, which seem to violate \( T \), but are caused by final-state or higher-order interactions, are called simulated (6) \( T \) violations (7).

We believe that the algebraic study of simulated effects is essential, from an experimental point of view, because it tells us not only the kinds of terms that may arise, but also their approximate dependence on energy and mo-

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(1) N. Cabibbo and M. Veltman: Weak Interactions, CERN 65-30.
(5) G. Leibbrandt: Can. Journ. Phys., 46, 1945 (1968). In this reference the terminology seeming \( T \) violation has been used.
(6) The occurrence of such triple scalar products is also a manifestation of simulated \( CPT \) violation. We are grateful to the referee for pointing this out to us.