## Photovoltages Larger than the Band Gap in Zinc Sulfide Crystals

S. G. Ellis, F. Herman, E. E. Loebner, W. J. Merz,* C. W. Struck,† and J. G. White

*RCA Laboratories, Princeton, New Jersey*
(Received January 13, 1958)

PENSAK[1] has discovered a photovoltage larger than the band-gap voltage in some films of cadmium telluride made by vacuum evaporation. A necessary condition for the effect is that the vapor be directed obliquely at the substrate on which it is condensed. The direction of the resulting photovoltage is related to the direction of evaporation.

X-ray diffraction examinations of the films disclosed only cubic cadmium telluride and neither x-ray diffraction nor polarizing microscope studies were able to detect a bulk anisotropy in the films related to the direction of vapor arrival. Nevertheless, the hypothesis was formed that if stacking faults existed in the film and if the normals to the planes of the stacking faults were oriented with respect to the direction of arrival of the vapor, then there would exist in the films a structural vector (the cadmium-tellurium bond vector perpendicular to the stacking fault) which could define the direction of the electric field produced by illumination. A consideration of the crystal field would indicate that there is a residual dipole layer at each stacking fault, and that at successive stacking faults the polarity has the same sign. We are therefore led naturally to the conclusion that the photovoltage developed at successive stacking faults would be additive, provided that the stacking faults are perpendicular to a common axis.

It was also believed that a clear test of these ideas could only be made on large crystals of the same structure type. Since suitable zinc sulfide crystals were available, the study was transferred to them.

These zinc sulfide crystals were clear fibers or platelets grown from the vapor. They contained random stacking faults. In some places there were ordered arrangements of stacking faults with periodicities of as many as 40 double layers. They were single crystals only in the sense that the [111] cubic and [0001] hexagonal directions were coincident and the boundaries between the phases were coherent. X-ray diffraction studies by the method of Coster, Knol, and Prins,[2] using tungsten $L_\beta$ radiation, showed that the growth direction was also that of the sulfur-zinc vector in the bonds perpendicular to the stacking faults.

Under ultraviolet illumination many of these crystals produce greater-than-band-gap photovoltages. While the stacking faults are often too closely spaced to permit resolution under the light microscope, the photovoltages were higher in the crystals in which microscope and x-ray studies indicated a higher number of stacking faults. The photovoltages were, in particular, high for crystals containing repetitive stacking faults. At room temperature fields of 100 volts $\mathrm{cm}^{-1}$ could be obtained. This corresponds to, very approximately, 0.1 volt per stacking fault. The direction of the electric field was the same as the growth direction, i.e., sulfur to zinc across the stacking fault.

While, historically, the experiments with evaporated cadmium telluride films[1,3] led to a successful search for a high photovoltage in zinc sulfide crystals, it would be incorrect to conclude that the photovoltages observed in the films are caused by stacking faults. The possibility remains, but there is no direct evidence for it.

These structural and electrical studies are being continued.

* Now at RCA Laboratories, Ltd., Zurich, Switzerland.

† At present, National Science Fellow at Princeton University, Princeton, New Jersey.

[1] L. Pensak, Phys. Rev. **109**, 601 (1958).
[2] Coster, Knol, and Prins, Z. Physik **63**, 345 (1930).
[3] B. Goldstein, Phys. Rev. **109**, 601 (1958).

---

## Chirality Invariance and the Universal Fermi Interaction*

E. C. G. Sudarshan, *Harvard University, Cambridge, Massachusetts*

and

R. E. Marshak, *University of Rochester, Rochester, New York*
(Received January 10, 1958)

WE have shown[1] that the imposition of the requirement of chirality invariance[2] on each covariant in the four-fermion interaction Hamiltonian leads to the essentially unique expression[3]:

$$G\{[\bar{A}\gamma_\mu(1+\gamma_5)B]^\dagger[\bar{C}\gamma_\mu(1+\gamma_5)D]+\text{H.c.}\} \qquad \text{(I)}$$

where $G$ is the coupling constant and $A$, $B$, $C$, $D$ are four Dirac *particle* fields. In the standard terminology of parity-conserving interactions, (I) represents the combination $V-A$ ($V$ is vector, $A$ is axial vector). We assumed that (I) holds between any two of the pairs[4] $np$, $\Lambda p$, $\mu^-\nu$, $e^-\nu$ (i.e., the *particles* are taken to be the neutron, proton, $\Lambda$ hyperon, negative muon, neutrino, and electron) with the same value of $G$. Such a universal $V-A$ four-fermion interaction is invariant under "combined inversion,"[5] yields a two-component neutrino of negative helicity, leads to conservation of leptons, and gives the maximal violation of parity—apart from conserving chirality.

In comparing the predictions of the $V-A$ theory with experiment, we pointed out at the Padua-Venice Conference that the theory could explain all beta-decay experiments (allowed as well as forbidden, parity-conserving as well as parity-nonconserving) except the electron-neutrino correlation[6] in $He^6$ and the electron asymmetry from polarized neutron decay,[7] all the muon experiments except the very preliminary experiment at Columbia[8] on the positron polarization from $\mu^+$ decay, the decay of the pion except for the apparent absence of the electron mode,[9] and all existing results on strange particle decays (except for the decay of the $\Xi$ hyperon which we discuss below). Since the conference, the validity of the $He^6$ experiment has been questioned,[10] the polarized neutron experiment has come down to a value consistent with the $V-A$ theory[11] and the helicity of the positron from $\mu^+$ decay has turned out[12] to be $+1$, as it should. There has been no change in the experimental situation with regard to the electron decay of the pion but it is clear that this very difficult experiment should be redone.

Since the universal $V-A$ four-fermion interaction is faring so well, it is worthwhile to spell out several other features of this theory which add to its attractiveness. (1) The $V-A$ theory is completely consistent with the latest experiment[13] on the radiative beta decay of the pion since it predicts 80 $sec^{-1}$ for the transition probability (which happens to be convergent in lowest order). This value is lower by a factor of $\sim(\mu/M)^2$ ($\mu$ is the pion mass, $M$ the nucleon mass) than the tensor prediction,[14] which Cassels *et al.* found difficult to reconcile with their experiment. (2) The $V-A$ theory predicts a large negative asymmetry parameter ($-0.88$) for the reaction $\Lambda\rightarrow p+\pi^-$, a result which is required by experiment.[15] This result follows from the fact that the $V-A$ theory yields an equivalent pseudovector coupling between the pion and the $(\Lambda p)$ pair.[16] A related prediction of the $V-A$ theory is that the neutral reaction $\Lambda\rightarrow n+\pi^0$ should have the same asymmetry parameter as its charged counterpart; this follows from the fact that the $V-A$ interaction stays the same whether we use the so-called charge-exchange or charge-retention order in (I). These results are unaltered by any final state interaction of the nucleon and the pion.[17] The qualification in these asymmetry predictions is that the meson renormalization effects are approximately the same for the $V$ and $A$ parts of the four-fermion interaction, a result which is implicit in the nearly equal contributions of the $V$ and $A$ interactions in beta decay.[18] (3) The mesonic decay of the charged $\Sigma$ hyperons can be explained without postulating direct interactions with $(\Sigma^\pm n)$ pairs; the strong coupling of the $\Sigma$ to the $\Lambda$ via the pion field provides a mechanism for the decay without introducing an unsymmetrical behavior[19] in the $\Sigma^+$ and $\Sigma^-$. Such an indirect mechanism for the decay of the charged $\Sigma$ hyperons also opens up the possibility of reduced asymmetry parameters for these decays, since additional renormalization effects enter the calculation[20]; it is not clear at present whether the failure to observe[15] an up-down asymmetry in $\Sigma^-$ decay resulting from the $\pi^-+p\rightarrow\Sigma^-+K^+$ reaction is due to a much smaller polarization of the $\Sigma^-$ (than the $\Lambda$ in the corresponding reaction) or to a much reduced asymmetry parameter. (4) To account for the decay of the $\Xi^-$ hyperon, we introduce a direct coupling (I) of the $(\Xi^-\Lambda)$ pair ($\Xi^-$ is assumed to be the *particle*) with the other four pairs already considered. The transition probability for the most rapid lepton decay mode: $\Xi^-\rightarrow\Lambda+e^-+\bar{\nu}$ is predicted to be $1.2\times10^8$ $sec^{-1}$, which is $\gtrsim5.5\%$ of the observed rate.[21] The asymmetry parameter for the observed mode $\Xi^-\rightarrow\Lambda+\pi^-$ is found to be $-0.96$. (5) We have remarked previously[1] that the $V-A$ theory possesses the virtue that it will predict preponderant muon decay of the $K$ meson even if the latter is a scalar particle in strong interactions. The evidence on the parity of the $K$ meson is still unclear.[22] (6) Tanikawa's attempt to develop a renormalizable four-fermion interaction by introducing an intermediate charged spinless boson[23] will not work with the $V-A$ theory because, as already stated, $V-A$ in the charge-exchange order still remains $V-A$ in the charge-retention order. It is therefore necessary to introduce an intermediate charged vector boson to derive a $V-A$ four-fermion interaction. This does not help with the renormalization[24] but there may be some advantage in postulating a chirality-invariant interaction between each fermion pair and a charged vector boson of large mass, as Schwinger[25] has done.

It is a pleasure to acknowledge useful conversations with Dr. C. J. Goebel and Mr. S. Okubo.

* Supported in part by the U. S. Atomic Energy Commission.

[1] E. C. G. Sudarshan and R. E. Marshak, *Proceedings of Padua-Venice Conference on Mesons and Newly Discovered Particles, September, 1957* [Suppl. Nuovo cimento (to be published)].

[2] The chirality transform of a Dirac spinor $\psi$ is $\gamma_5\psi$ (we use a Hermitian $\gamma_5$ so that $\gamma_5^2=+1$). S. Watanabe gave the first systematic treatment of the properties of the chirality operator [Phys. Rev. **106**, 1306 (1957)], although the term originated with A. E. S. Eddington [*Fundamental Theory* (Cambridge University Press, New York, 1949), p. 111.]

[3] R. P. Feynman and M. Gell-Mann [Phys. Rev. **109**, 193 (1958)] have independently arrived at this expression on the basis of a two-component spinor theory for all spin $\frac{1}{2}$ particles and no gradients in the interaction Hamiltonian; however, this theory requires the two-component wave function to satisfy a second order equation which raises certain difficulties of principle (quantization according to the usual rules, effect of strong interactions, etc.). More recently, J. J. Sakurai has obtained expression (I) by requiring the invariance of the four-fermion Hamiltonian under separate reversal of the sign of the mass in the Dirac equation for each fermion; this condition is completely equivalent to the condition of chirality invariance. We are indebted to the authors for sending us preprints of their papers.

[4] M. Gell-Mann was the first to add the $(\Lambda p)$ pair to the Puppi triangle in *Proceedings of the International Conference on Elementary Particles, Pisa, 1955* [Suppl. Nuovo cimento 4, 848 (1956)].

[5] In Landau's terminology [see L. Landau, Nuclear Phys. **3**, 127 (1957)].

[6] B. M. Rustad and S. L. Ruby, Phys. Rev. **97**, 991 (1955).

[7] Burgy, Epstein, Krohn, Novey, Raboy, Ringo, and Telegdi, Phys. Rev. **107**, 1731 (1957).

[8] Coffin, Berley, Garwin, Lederman, and Weinrich (private communications from P. T. Matthews and M. Gell-Mann).

[9] H. L. Anderson and C. M. G. Lattes [Nuovo cimento (to be published)] give for the ratio of the $e\nu$ to the $\mu\nu$ modes the value $(-0.4\pm9)\times10^{-6}$.

[10] C. S. Wu (private communication); the experiment must still be redone.

[11] Burgy, Krohn, Novey, Ringo, and Telegdi find for the asymmetry $0.15\pm0.08$ (private communication from V. L. Telegdi).

[12] Culligan, Frank, Holt, Kluyver, and Massam, Nature (to be published).

[13] Cassels, Rigby, Wetherell, and Wormald, Proc. Phys. Soc. (London) **A70**, 729 (1957).

[14] S. B. Treiman and H. W. Wyld [Phys. Rev. **101**, 1552 (1956)] had already observed this feature of the axial vector theory although they did not utilize it because they accepted the $He^6$ experiment; the same $(\mu/M)^2$ factor is introduced by the vector theory.

[15] Crawford, Cresti, Good, Gottstein, Lyman, Solmitz, Stevenson, and Ticho, Phys. Rev. **108**, 1102 (1957); the sign has not been determined because the sign of the polarization of the $\Lambda$ is unknown. Measurements of the sign of the asymmetry will decide whether our choice of particles for the baryons is correct.

[16] J. J. Sakurai, Phys. Rev. **108**, 491 (1957); we are indebted to Mr. Sakurai for a conversation on this point.

[17] If the isotopic spin selection rule, $\Delta I=\frac{1}{2}$, holds.

[18] The absolute renormalization through the strong interactions is small for the $V$ interaction as seen from the close numerical agreement between the vector coupling coefficient in $\beta$ decay and $\mu$ decay (see Feynman and Gell-Mann, reference 3).

[19] The postulation of a direct $V-A$ interaction with the $(n\Sigma^+)$ pair presumably leads to difficulty with the decay of the $\Xi^-$ hyperon (see Feynman and Gell-Mann, reference 3). Our addition of the $(\Xi^-\Lambda)$ pair does not lead to the unobserved reaction $\Xi^-\rightarrow n+\pi^-$ (see below).

[20] A direct $V-A$ coupling with the $(\Sigma^-n)$ pair, handled in the same way as for the $\Lambda$ decay, predicts an asymmetry parameter of $-0.98$; the asymmetry parameter for $\Sigma^-$ decay predicted by the indirect mechanism is being calculated by F. Salzman.

[21] *Proceedings of the Seventh Annual Rochester Conference on High-Energy Physics* (Interscience Publishers, Inc., New York, 1957), Chap. VI. The decay modes of the $\Xi$ can also be derived indirectly through $K$-meson coupling with the $\Lambda$.

[22] C. J. Goebel, Phys. Rev. (to be published).

[23] Y. Tanikawa, Phys. Rev. **108**, 1615 (1957).

[24] H. Umezawa, Progr. Theoret. Phys. (Japan) **7**, 551 (1952); R. J. N. Phillips, Phys. Rev. **96**, 1678 (1954). One of us (E.C.G.S.) acknowledges an illuminating discussion with Mr. S. Glashow on the renormalizability of vector meson theories.

[25] J. Schwinger, Ann. Phys. **2**, 407 (1957); this idea has also been suggested by S. Watanabe (private communication).