## Brief Reports

*Brief Reports are short papers which report on completed research which, while meeting the usual* **Physical Review** *standards of scientific quality, does not warrant a regular article. (Addenda to papers previously published in the* **Physical Review** *by the same authors are included in Brief Reports.) A Brief Report may be no longer than 3½ printed pages and must be accompanied by an abstract. The same publication schedule as for regular articles is followed, and page proofs are sent to authors.*

# Positron annihilation in metals with broken reflectional symmetry

A. Vilenkin
*Physics Department, Tufts University, Medford, Massachusetts 02155*
(Received 14 September 1983)

An experiment is proposed to test the recent suggestion that the conduction electrons in some metals can spontaneously develop a nonzero average helicity. The photon pair momentum distribution resulting from positron annihilation in such metals is shown to be asymmetric in the direction of positron polarization. This asymmetry should be easily detectable by present experimental techniques.

It has been recently suggested[1,2] that reflectional symmetry of the electron Fermi liquid in some metals can be spontaneously broken as a result of an effective exchange interaction between electrons. If the interaction of the form $-(\vec{p}\cdot\vec{p}')(\vec{\sigma}\cdot\vec{\sigma}')$ is strong enough, it may become energetically favorable for the electrons to develop a nonzero average helicity, $h=\langle\vec{\sigma}\cdot\hat{p}\rangle\neq 0$. Here, $\vec{\sigma}$ is the electron spin, $\vec{p}$ is its (quasi)momentum, and $\hat{p}=\vec{p}/p$. Chudnovsky has suggested[3] that spontaneous reflectional-symmetry violation (SRSV) can explain the unusual properties[4] of the compound $TiBe_2$. A direct experimental test of SRSV can be based on a proportionality between polar and axial vectors. For example, an electric current $\vec{j}$ parallel or antiparallel to a magnetic field $\vec{B}$ can arise in a number of nonequilibrium situations[2] (e.g., if $\vec{B}$ changes in time or in the presence of an electromagnetic wave). However, as shown in Ref. 2, effects of this sort are extremely small, even in the case of strong symmetry violation ($h\sim 1$). In this paper, I suggest a straightforward test for SRSV using electron-positron annihilation.

The physics of $e^+e^-$ annihilation in metals has been reviewed in detail by West.[5] Positrons are emitted by radioactive sources with energies of the order 0.5 MeV. However, they are rapidly thermalized by collisions with conduction electrons and come practically to rest on a time scale $\sim 3$ psec, which is about 100 times smaller than the typical annihilation time. Positrons emitted from sources such as $^{64}Cu$ or $^{22}Na$ are partially polarized parallel to their direction of motion. A substantial amount of this polarization persists throughout the thermalization until annihilation. The dominant annihilation process is the two-photon annihilation, $e^+e^-\to\gamma\gamma$. For our purposes, the most important feature of this process is its strong dependence on polarization: Annihilation of nonrelativistic $e^+$ and $e^-$ can occur only if their spins are antiparallel. (To be more exact, the ratio of the cross sections for spins parallel to spins antiparallel is 1:372.)

Suppose the positron is polarized along the $z$ axis ($s_z=\frac{1}{2}$). Then it can annihilate only electrons with $s_z=-\frac{1}{2}$. If electrons have, say, positive helicity, then electrons with $s_z=-\frac{1}{2}$ are moving preferentially in the negative $z$ direction, and we expect that the momentum distribution of the resulting photon pairs will be asymmetric. There will be more pairs with $p_z<0$ than with $p_z>0$. To estimate the expected asymmetry, we shall find the photon pair momentum distribution $\Gamma(\vec{p})$ in a simple model[2] of SRSV. [$\Gamma(\vec{p})d^3p$ is the number of photon pairs emitted in momentum space interval $d^3p$.]

The annihilation rate is practically independent of electron velocity $v$ (the cross section is $\sigma\propto v^{-1}$ and the rate is $\propto\sigma v=\text{const}$), and thus, for positrons completely polarized in the $z$ direction,

$$\Gamma(\vec{p})\propto n_{\vec{p}\downarrow}\ , \tag{1}$$

where $n_{\vec{p}\downarrow}$ is the occupation number of the electron state with momentum $\vec{p}$ and $s_z=-\frac{1}{2}$. In the model of Ref. 2, the electron distribution is described by the matrix

$$(n_{\vec{p}})_{\alpha\beta}=\tfrac{1}{2}(\delta_{\alpha\beta}+\vec{\sigma}_{\alpha\beta}\cdot\hat{p})f_+(\epsilon_p)+\tfrac{1}{2}(\delta_{\alpha\beta}-\vec{\sigma}_{\alpha\beta}\cdot\hat{p})f_-(\epsilon_p)\ , \tag{2}$$

where $\vec{\sigma}_{\alpha\beta}$ are Pauli matrices,

$$f_\pm(\epsilon_p)=f(\epsilon_p\mp\lambda)\ , \tag{3}$$

$f(\epsilon)=\{\exp[(\epsilon-\zeta)/T]+1\}^{-1}$ is the Fermi function, $\epsilon_p=p^2/2m$, $\zeta$ is the Fermi energy, and $\lambda$ is the energy parameter characterizing the symmetry breaking. In the general case, $\lambda$ is expected to be $\sim\zeta$. From Eqs. (1) and (2) we obtain

$$\Gamma(\vec{p})\propto\tfrac{1}{2}(f_++f_-)-\tfrac{1}{2}\hat{p}_z(f_+-f_-)\ . \tag{4}$$

One of the quantities that can be measured directly in positron annihilation experiments is the distribution of one component of the pair momentum

$$N(p_z)\propto\int\Gamma(\vec{p})\,dp_x\,dp_y\ . \tag{5}$$

An explicit expression for $N(p_z)$ can be found in the case $\lambda\ll\zeta$, $T=0$:

$$N(p_z)\propto\int[f(\epsilon_p)+\lambda\hat{p}_zf'(\epsilon_p)]\,dp_x\,dp_y=2\pi m(\zeta-p_z^2/2m-\lambda p_z/p_F)\ , \tag{6}$$

 

where $p_F$ is the Fermi momentum $p_F=(2m\zeta)^{1/2}$. The maximum of the curve $N(p_z)$ is at $p_z=(\lambda/2\zeta)p_F$, while for a reflectionally symmetric state it is at $p_z=0$.

Another convenient characteristic of the asymmetry is $\delta=(N_- - N_+)/(N_- + N_+)$, where $N_+$ and $N_-$ are the total numbers of photon pairs with $p_z>0$ and $p_z<0$, respectively. A simple integration of Eq. (6) gives

$$\delta=\frac{3}{4}\lambda/\zeta \ . \tag{7}$$

Although Eqs. (6) and (7) were obtained for $\lambda \ll \zeta$, it is clear from the calculation that for $\lambda\sim\zeta$, $\delta$ is $\sim 1$. We expect also that the order-of-magnitude relation $\delta\sim\lambda/\zeta$ applies not only in our simple model, but in the general case of SRSV as well.

Equations (6) and (7) were derived assuming complete positron polarization in the $z$ direction. In the general case, $\lambda$ in these equations should be replaced by $\lambda P_z$, where $P_z\leq 1$ is the positron polarization.

For $\lambda/\zeta$ not too small, the asymmetry due to SRSV should be easily detectable using the standard positron annihilation apparatus.[6] Unfortunately, for $TiBe_2$, which is one of the possible candidates for SRSV, $\lambda/\zeta$ is expected to be small,[3] $\sim 10^{-3}-10^{-4}$. (In fact, if the SRSV model for $TiBe_2$ is correct, it is the smallness of $\lambda$ which is responsible for the interesting behavior of this compound. Materials with $\lambda\sim\zeta$ are not expected to exhibit any kind of exotic behavior in terms of their equilibrium properties.[1,2] The strength of positron sources precludes making the asymmetry test for $TiBe_2$ at this time. However, in the future with the advent of intense positron sources it may be possible to make this test.

I am grateful to Leon Gunther for pointing out to me that positron annihilation may be used to detect SRSV, and to Eugene Chudnovsky for his very helpful comments on the manuscript.

[1]I. A. Achiezer and E. M. Chudnovsky, Phys. Lett. 65A, 433 (1978).
[2]E. M. Chudnovsky and A. Vilenkin, Phys. Rev. B 25, 4301 (1982).
[3]E. M. Chudnovsky, Phys. Lett. 93A, 97 (1982).
[4]E. P. Wohlfarth, Comments Solid State Phys. 10, 39 (1981).
[5]R. N West, Adv. Phys. 22, 263 (1973).

[6]It should be noted that in polycrystals different crystallites will have opposite signs of electron helicity, and their contributions to the asymmetry will tend to cancel out. Therefore the experiment should be done using a monocrystal. I am grateful to E. Chudnovsky for pointing this out to me.