SEARCH FOR C NONCONSERVATION IN ELECTRON-POSITRON ANNIHILATION*

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In this Letter we report the results of an experiment designed to search for the three-photon decay of $^1S_0$ electron-positron states; like the decay $\pi^0 \to 3\gamma$, this annihilation mode is forbidden by charge-conjugation invariance only.[1] Recently an upper limit for the branching ratio $R = (\pi^0 \to 3\gamma)/(\pi^0 \to 2\gamma)$ of $R \leq 5\times10^{-6}$ (90% confidence level) was obtained experimentally by Duclos et al.[2] The observation of the C-forbidden 3γ decay is greatly complicated in the case of positron annihilation, on account of the abundant, allowed, 3γ decay mode of $^3S_1$ positronium. When positronium is formed in a gas, the ratio of the C-allowed three- to two-photon decays can be made to approach the spin-averaged free-positron decay ratio of 1/372, by quenching the triplet state[1] with the addition of NO gas, for example, but this represents a lower limit.

Our experiment is designed to separate the C-forbidden 3γ decay of $^1S_0$ from the allowed 3γ decay of the $^3S_1$ state by studying the angular distribution of the three photons. Because of Bose statistics, the C-nonconserving $^1S_0 \to 3\gamma$ rate must vanish for the case of the three photons emerging symmetrically (120°, 120°, 120°), independent of the assumed form of the C-nonconserving interaction.[3] Essentially, we measure the 3γ rate at the symmetric configuration and at some other set of angles [(60°, 150°, 150°) and (90°, 120°, 150°) in the actual setup]; the ratio of these two rates will change when the relative abundance of triplet-to-singlet annihilations is changed by NO quenching, if and only if there is some C-nonconserving 3γ contribution from the $^1S_0$ state. It is to be noted that the 3γ angular distributions do not depend on the radial wave function of the positron-electron system; only the magnitudes of the rates do. In our argument it is thus unimportant whether the annihilation is from a free positronium atom or from some other positron-electron system.

For a quantitative evaluation of our measurements, we make use of the recently proposed C-nonconserving phenomenological point interactions[4-6] that can cause the decay $^1S_0 \to 3\gamma$. Unfortunately, the simpler of these interactions (with five derivatives) yields identically vanishing matrix elements.[7] The simplest nonvanishing forms are proportional to those suggested by Berends[5] and Weisberg[6]: The parity-conserving (C- and T-nonconserving) interaction is given by

$$\mathcal{L}_I^{(P)}(x) = g\left(\frac{1}{2m}\right)^8 \bar{\psi}\gamma_5\gamma_\mu\psi G_{\alpha\beta}F_{\alpha\beta,\gamma\delta}F_{\mu\gamma,\delta}, \quad (1)$$

and the time-reversal-invariant interaction is

$$\mathcal{L}_I^{(T)}(x) = g\left(\frac{1}{2m}\right)^8 \bar{\psi}\gamma_5\gamma_\mu\psi F_{\alpha\beta}F_{\alpha\beta,\gamma\delta}F_{\mu\gamma,\delta}, \quad (2)$$

where $G_{\mu\nu} = \frac{1}{2}\epsilon_{\mu\nu\rho\sigma}F_{\rho\sigma}$, $F_{\mu\nu} = A_{\nu,\mu} - A_{\mu,\nu}$ ($F_{\mu\nu}$ is the electromagnetic field operator), and ψ is the electron field operator. These two Lagrangian densities predict identical 3γ angular distributions and total rates for the decay $^1S_0 \to 3\gamma$. (They differ in their polarization correlation prediction.) Similar interactions also predict a C-nonconserving $\pi^0 \to 3\gamma$ decay.[5,6]

From these Lagrangians one obtains the $^1S_0 \to 3\gamma$ angular distribution $d\Gamma_S^{3\gamma}$ and the decay rate $\Gamma_S^{3\gamma}$, using the positronium ground-state $^1S_0$ wave function:

$$d\Gamma_S^{3\gamma} = \frac{g^2\Gamma_S^{2\gamma}}{8\alpha^2(2\pi)^6}(\omega_1\omega_2\omega_3)^3(\sum s_i)^2\Big[\sum_{1\to2\to3}(\tfrac{1}{2}-\omega_3)^2(\omega_1-\omega_2)^2\Big]d\theta_{12}d\theta_{13}d\Omega_1 d\varphi_1 \quad (3)$$

and

$$\Gamma_S^{3\gamma} = \frac{g^2\Gamma_S^{2\gamma}}{64\alpha^2\pi^4}\int_0^{1/2}d\omega_1\int_{\frac{1}{2}-\omega_1}^{1/2}(\omega_1\omega_2\omega_3)^2(\sum s_i)^2\Big[\sum_{1\to2\to3}(\tfrac{1}{2}-\omega_3)^2(\omega_1-\omega_2)^2\Big]d\omega_2 \approx 2.4\times10^{-6}g^2\Gamma_S^{2\gamma} \quad (4)$$

in terms of $\Gamma_S^{2\gamma}$, the C-allowed $^1S_0 \to 2\gamma$ positron rate. The ω_i are the photon energies in units of

$2m_ec^2$; $s_1 = \sin\theta_{23}$, where θ_{23} is the angle between photons 2 and 3; the m in Eqs. (1) and (2) has been taken to be m_e. The C-allowed ${}^3S_1 \rightarrow 3\gamma$ angular distribution $d\Gamma_T{}^{3\gamma}$ and decay rate $\Gamma_T{}^{3\gamma}$ were given by Ore and Powell[8] as

$$d\Gamma_T{}^{3\gamma} = \frac{8\alpha\Gamma_S{}^{2\gamma}}{3(2\pi)^4}(\omega_1\omega_2\omega_3)^{-1}\sum_{i=1}^{3}\omega_i{}^2(\tfrac{1}{2}-\omega_i)^2 d\theta_{12}d\theta_{13}d\Omega_1 d\varphi_1 \tag{5}$$

and

$$\Gamma_T{}^{3\gamma} = \frac{4\alpha\Gamma_S{}^{2\gamma}}{3\pi^2}\int_0^{1/2}d\omega_1\int_{\frac{1}{2}-\omega_1}^{1/2}\sum_{1\rightarrow2\rightarrow3}(\tfrac{1}{2}-\omega_1)^2/(\omega_2\omega_3)^2 d\omega_2 = 0.898\times10^{-3}\Gamma_S{}^{2\gamma}. \tag{6}$$

These distributions [Eqs. (3) and (5)] are plotted schematically in Fig. 1 for infinitesimal circular counters, normalized to their angular average.

The apparatus for the present experiment consisted of a thin-walled gas chamber containing a Cu^{64} source, six NaI(Tl) scintillation detectors, and multiple-coincidence electronics. The source chamber was a 0.75-in. diameter 4-in.-long stainless steel (s.s.) tube, of 0.01-in. wall thickness, attached to a gas system which provided either pure SF_6 gas or a mixture of SF_6 plus 1% NO at 180 psi. The positron source was an activated 0.25-in.-diameter copper foil, 0.1 or 0.25 mil thick. The foil was point soldered to a 0.008-in.-diameter s.s. wire and was suspended in the center of the chamber.

The 1.5-in.-diameter by 2.0-in.-long NaI(Tl) crystals were coupled to RCA C70101-B photomultipliers, and were placed with their faces 5.0 in. from the center of the source chamber, positioned as shown in Fig. 2, behind lead collimators. Identical lead collimators surrounded the chamber completely, providing a cylin-

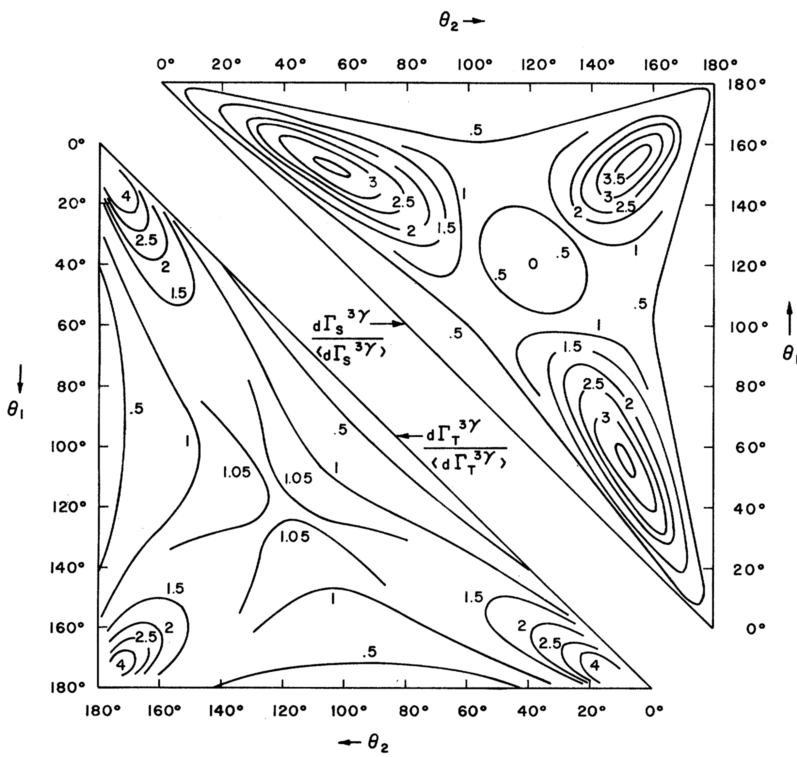

FIG. 1. The angular distributions $d\Gamma_S{}^{3\gamma}$ and $d\Gamma_T{}^{3\gamma}$ for the C-forbidden ${}^1S_0 \rightarrow 3\gamma$ and the C-allowed ${}^3S_1 \rightarrow 3\gamma$ annihilation, normalized to their angular averages, are plotted as contour maps against the two angles $\theta_1\theta_2$ ($\theta_3 = 360° - \theta_1 - \theta_2$).

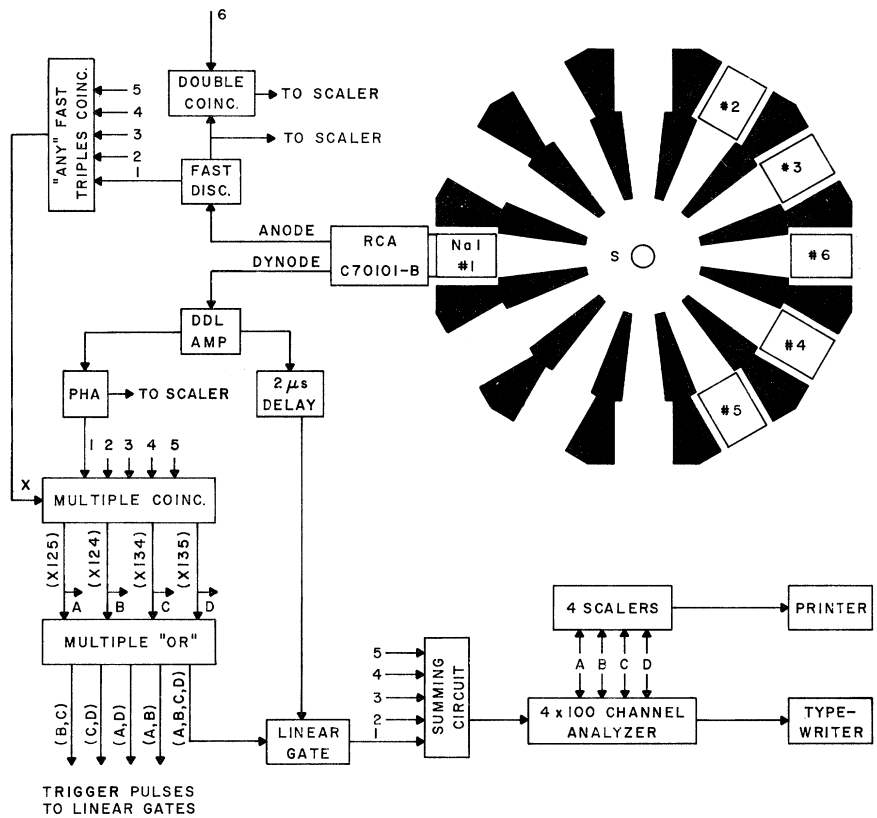

FIG. 2. Schematic layout of the experimental setup and block diagram of the electronics used. The black area around the detectors is the outline of the lead-collimator system used to reduce counter-to-counter scattering.

drically symmetrical background scattering geometry.

The block diagram of the electronics is also shown in Fig. 2. The four summed triple-coincidence energy spectra were routed into a split-memory 400-channel analyzer, and four scalers counted the total number of triple coincidences (routing pulses). A fifth scaler provided a continuous record of singles rates, "window" rates, doubles rates, and total fast-triples rates on a time-shared basis.

A typical run consisted of a two-hour period of counting with pure SF_6 in the chamber, followed by about 20 h of counting with a mixture of SF_6 plus 1% NO. 60 such runs, using 1-mCi Cu^{64} sources each, provided a total of about 10^5 quenched counts in each of the four triples configurations, and five times as many unquenched counts.

Figure 3 shows the quenched and unquenched sum spectra obtained in the symmetrical configuration, the sum peak at 1.0 MeV indicating clearly that one is observing 3γ positron-electron decays. The other configurations give rise to similar curves. Since the background fractions are small, as indicated by the similarity between the quenched and unquenched curves, in the final analysis we have used the total areas under these spectra, as obtained by the routing pulses, rather than the photopeaks.

If we let $P_T(\theta_1\theta_2\theta_3)\epsilon_{123}{}^T$ be the probability that three photons are counted by the counter configuration at $(\theta_1\theta_2\theta_3)$, when there is a 3γ annihilation from triplet overlap, where $\epsilon_{123}{}^T$ is the efficiency of the system and P_T stands for the integral of $d\Gamma_T{}^{3\gamma}/\Gamma_T{}^{3\gamma}$ over the finite counter faces, the counting rate for the unquenched gas is given by

$$E^{3\gamma}(\theta_1\theta_2\theta_3)=N[TP_T(\theta_1\theta_2\theta_3)\epsilon_{123}{}^T + (1-T)bP_S(\theta_1\theta_2\theta_3)\epsilon_{123}{}^S]. \quad (7)$$

In this equation T is the fraction of triplet and $(1-T)$ of singlet annihilation, P_S is defined like

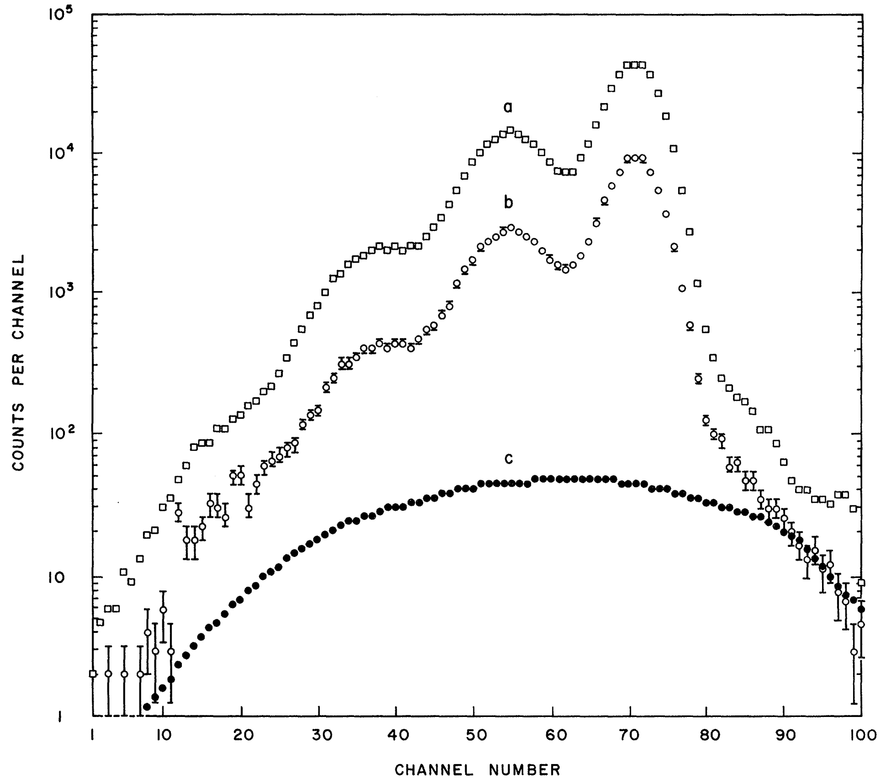

FIG. 3. Quenched (a) and unquenched (b) sum spectra obtained as shown in Fig. 2, for the symmetrical configuration A; the computed background (c), as discussed in the text, is also shown. The scale is one MeV per 100 channels with zero supressed by 30 channels. Similar curves were obtained for the other counter configurations.

P_T for the singlet 3γ decays, N is the source strength, and b is the C-forbidden 3γ to 2γ branching ratio $b=\Gamma_S{}^{3\gamma}/\Gamma_S{}^{2\gamma}$. Let Q be the quenching ratio, i.e., let the total triplet annihilation in the NO quenched system be T/Q. We then construct counting-rate ratios

$$R=\frac{E^{3\gamma}(\theta_1\theta_2\theta_3)}{E^{3\gamma}(120°, 120°, 120°)},$$

and form

$$\frac{\Delta}{\Sigma}=\frac{R_Q-R_U}{R_Q+R_U},$$

where R_Q and R_U are the quenched versus unquenched counting-rate ratios, thus eliminating N and the efficiencies, since $\epsilon_{123}{}^T\approx\epsilon_{123}{}^S$ over the small counter faces. From the above we can obtain the branching ratio

$$b=\frac{2Q}{(Q-1)}\frac{P_T(\theta_1\theta_2\theta_3)}{P_S(\theta_1\theta_2\theta_3)}\frac{T}{Q}\frac{\Delta}{\Sigma}, \tag{8}$$

using $P_S(120°, 120°, 120°)\approx 0$ and $b\ll 1$.

Q is measured by comparing the quenched and unquenched 3γ rates at (120°, 120°, 120°), and T/Q is obtained by comparing experimentally the quenched rate at (120°, 120°, 120°) with the rate obtained from the same source surrounded by a metal sandwich, where $T=1/372$. We obtained $Q=33\pm 6$ and $T/Q=(1/372)(1.06\pm 0.06)$. Using these values and the theoretical distributions, including a $P_S(120°, 120°, 120°)>0$ due to finite counter faces, we obtain

$$b=(2.7\pm 0.2)\times 10^{-3}(\Delta/\Sigma)_C$$

and

$$b=(5.4\pm 0.4)\times 10^{-3}(\Delta/\Sigma)_{B,D}, \tag{9}$$

where $(\Delta/\Sigma)_C$ and $(\Delta/\Sigma)_{B,D}$ are the measured (and corrected) values of Δ/Σ for the configurations C (60°, 150°, 150°) and B and D (90°, 120°, 150°) [see Fig. 2].

It is important to note that the values in Eqs. (9) are not too sensitive to the exact form of the interaction Lagrangian, since any $d\Gamma_S{}^{3\gamma}$

having to vanish at (120°, 120°, 120°) and (180°, 180°, θ) will peak somewhere around (60°, 150°, 150°) unless the Lagrangian is very complicated.

The quantities $(\Delta/\Sigma)_{\rm expt.}$ for the configurations C and B and D were measured for the 61 separate runs of the experiment. The standard deviation of the separate measurements was found to be within 10% of that computed from counting statistics alone. The mean values are given in Table I; these values must be corrected for systematic errors before calculating b from Eqs. (9). Table I shows the corrections to be made to Δ/Σ for the angular configurations measured; these corrections were calculated by taking into account the following effects leading to systematic errors:

Geometric effect.— The three-photon acceptance for the configurations of interest differ from one another as a function of effective source height above the symmetry plane; the spatial distribution of the three γ's changes between the quenched and unquenched case, since approximately 10% of the positrons annihilate in the source foil and in the wire supporting the foil; the correction is due to the combination of these two effects and was determined numerically by a computer program.

Source decay effect.— This is due to the change in the efficiency of the triple-coincidence system during the decay of the Cu^{64} source in each run, since the phototube gains vary with counting rate and the side-channel energy discriminators could not be set to zero. The gain variation with counting rate was measured for each counter, and the net effect on the coincidence efficiency was computed for each configuration in an average run.

Accidental coincidences.— We differentiate two major sources for the accidental rate: (a) the genuine accidental triples rate $A=3N_1N_2N_3\tau$, where N_i are the singles rates in the energy windows and τ is the resolving time used, $\tau=7.1\times10^{-9}$ sec and (b) the accidental rate due to a true but unwanted double coincidence plus an accidental in a third counter. The true double coincidences stem from (b_1) a β^+ bremsstrahlung photon followed by one of the γ's from the decay ${}^1S_0\to2\gamma$, (b_2) two of the three γ's from the decay ${}^3S_1\to3\gamma$, (b_3) the scattering in the source holder of one of the two γ's from the decay ${}^1S_0\to2\gamma$, and (b_4) scattering of a photon from one counter to another [only feasible in our geometry for the (60°, 150°, 150°) configuration]. To compute these accidental backgrounds we measured the doubles spectra between all pairs of counters and obtained the triples background rate by folding these spectra with the appropriate third counter normalized window spectrum and multiplying the result by $2N\tau$. (This background spectrum is plotted in Fig. 3 for the configuration A.)

True triples background.— This can arise from a combination of (b_3) and (b_4) (see previous paragraph) in time coincidence. This unwanted true triple effect was estimated by using in place of Cu^{64} a Sr^{85} source, which emits a single 0.514-MeV γ ray and is, therefore, an excellent imitator of the ${}^1S_0\to2\gamma$ decay photons. The counter-to-counter scattering (b_4) was thus measured directly and the triples rate then computed ($b_3\times b_4$). We could, in principle, obtain an unwanted true triple event from the allowed decay ${}^1S_0\to4\gamma$, but we estimate this mode to contribute negligibly to Δ/Σ.

Using the corrections of Table I, we obtain from Eqs. (9) $b=(-11.3\pm6.2)\times10^{-6}$ when using configuration C, and $b=(10.8\pm11.9)\times10^{-6}$ for the average of the configurations B and D. We do not take an average of these, since the

Table I. Experimental Δ/Σ values and systematic corrections to Δ/Σ with estimated errors.

	Configuration C	Configurations B and D averaged
$(\Delta/\Sigma)_{\rm expt.}$	-0.0026 ± 0.0019	$+0.0038\pm0.0018$
Geometric effect	-0.0007 ± 0.0003	0.0000 ± 0.0003
Source decay effect	-0.0014 ± 0.0006	-0.0020 ± 0.0006
Accidental coincidences	$+0.0018\pm0.0010$	$+0.0038\pm0.0010$
"True triples" background	$+0.0019\pm0.0005$	0
Total systematic correction	$+0.0016\pm0.0013$	$+0.0018\pm0.0012$
Corrected Δ/Σ	-0.0042 ± 0.0023	$+0.0020\pm0.0022$

errors are correlated, the A-configuration counting rate being used in both; also, should these answers turn out to be significantly different from each other in an improved experiment, this might reflect a different angular distribution $d\Gamma_S{}^{3\gamma}$. Since $b \geq 0$, one can estimate from the C-configuration result that $b \leq 2.8\times10^{-6}$ with a 68% confidence limit. Such an upper limit, if the Lagrangians of Eq. (1) or (2) are to be taken seriously, corresponds to $g \leq 1.08$, when using the mass of the electron for m.

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[6]H. L. Weisbert, University of California Radiation Laboratory Report No. UCRL-16801, 1966 (unpublished).

[7]An error occurs in Eq. (7) of Ref. 4, where the fourth components of the photon momenta, $k_\mu{}^{(i)}$, were left out of the scalar products of the form $k_\mu{}^{(1)}k^{(2)\mu}$; the corrected expression vanishes identically.

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PHOTOPRODUCTION OF WIDE-ANGLE ELECTRON PAIRS FROM CARBON*

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Measurements of the photoproduction of wide-angle electron pairs from carbon in the energy range 600 to 2000 MeV are reported. The results agree with the predictions of quantum electrodynamics substantially better than the previously reported results, based on part of the data presented here, which showed a discrepancy of 2.3 standard deviations.

The photoproduction of wide-angle electron pairs from carbon has been measured at the Cornell electron synchrotron, at peak bremsstrahlung energies ranging from 600 to 2000 MeV. Two series of measurements were made: The first, or "old," series[1] has already been reported; the second, "new," series was carried out since that report.

The apparatus is shown in Fig. 1. The bremsstrahlung beam from the synchrotron, produced by electrons incident on a 0.1-radiation-length tungsten target, was collimated and passed through a region of sweeping field, a thin-plate ion chamber, and the carbon target (usually 2.5 g/cm^2 thick), after which it was stopped in uranium. The beam spot at the target was half an inch in diameter. The ion chamber was used as a beam-intensity monitor during runs. Before and after every run it was calibrated against a thick quantameter placed in the beam at the target position. The electron and positron passed through symmetrically placed apertures defined by uranium into a region of uniform magnetic field. The trajectories were recorded in thin-plate aluminum spark chambers and a set of lead and brass "shower" chambers. A sixfold coincidence of the counters $L_1L_2L_3R_1R_2R_3$ shown in Fig. 1 triggered the spark chambers, registering a "pair." For the "new" series, some changes were made in the apparatus. Counters L_3 and R_3 were moved downstream to the center of the magnet in order to decrease the singles rates in them. In the "old" configuration, the beam intensity was limited by the instantaneous rates in L_3 and R_3, typically held to 5 Mc/sec. In both series of runs, the duty cycle of L_3 or R_3 was continuously monitored and the beam intensity adjusted to keep it constant. The shower chambers were rebuilt to record each shower of the pair in an independent chamber; the number of gaps was increased and the thick-