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[10]A factor of two in the upper bound of $\sigma_W B$ will change the confidence levels for the nonexistence of W (assuming the cross sections given by Ref. 7). See Ref. 3.

EXPERIMENTAL SEARCH FOR CHARGE CONJUGATION NONCONSERVATION IN $^1S_0$ STATE POSITRONIUM DECAY

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The invariance under charge conjugation C in electromagnetic interactions is generally accepted, and up to now no experimental evidence of violation has been reported. The only experimental test of good statistics reported thus far has been that by Cline and Dowd,[1] who searched for the $\pi^0 \rightarrow 3\gamma$ decay mode and set an upper limit of 3.8×10^{-4} on the branching ratio $(\pi^0 \rightarrow 3\gamma)/(\pi^0 \rightarrow 2\gamma)$.

Earlier, Schechter[2] suggested that the decay of $^1S_0$ state positronium would serve as a test of C invariance. However, calculations by the present authors showed that the experiment as suggested by Schechter was not feasible. Therefore, an experiment was designed to search for the three-quantum decay of $^1S_0$ state positronium. The method consisted of a measurement in liquid oxygen and in aluminum of the relative number of three-quantum coincidence events having an energy sum of 1.02 MeV.

To observe the three-quantum events, three 2-in.-diameter by 2-in.-long NaI(Tl) photomultiplier detectors were mounted in a plane at 120° to one another and 3 in. from the mean position of a positron source. Each detector was shielded with lead so that a Compton-scattered photon from one detector would not produce a pulse in either of the other two. Three-quantum decay kinematics allows one to determine the maximum and minimum energy any one photon can deposit in a detector for a given set of angles. In the above arrangement, this is between 120 and 440 keV. The energy discrimination window of each detecting channel was set for these values and the output presented to a triple-coincidence system ($2\tau = 100$ nsec, where τ is resolution time). To identify the three-quantum events, the pulses from the three detectors were added and the resulting pulse was presented to a multichannel analyzer gated by the triple-coincidence signal.

The source of positrons used was Cu^{64}. Each source consisted of a 0.312-in.-diameter by 0.0002-in.-thick copper disk, mounted on a rigidly supported frame and immersed in a Dewar containing liquid oxygen, with either an aluminum-oxygen or an oxygen-aluminum sandwich configuration of equal thickness. A set of data consists of a measurement of the amount of three-quantum events present in the two different sandwich configurations, each started with equal positron activities ($\sim 2\times10^5$ disintegrations/sec) and counted for an equal clock time of about 21 hr. A typical set of data is presented in Fig. 1. The shaded area in each spectrum represents the number of true three-quantum annihilation events in which the three detected photons have deposited their total energy of 1.02 MeV. From considerations of the counting statistics and systematic errors, the system can detect a 10% change in intensity relative to aluminum.

Interpretation of the present data requires three reasonable assumptions based on experimentally established facts:

(1) No positronium is formed in aluminum. Held and Kahana[3] have shown that no electron-positron "bound state" can be formed in a metal. Therefore, all the three-quantum events in aluminum come from the fraction (1/372) of free-positron annihilation resulting from slow electron-positron collisions with statistically distributed spins.[4] The three-quantum annihilation probability in metals measured by Basson[5] and Bertolaccini, Bussolati, and Zappa[6] has confirmed this value.

(2) It has been established by lifetime measurements,[7] gamma-spectrum method,[8] and angular-distribution measurements[9] that $^3S_1$ state positronium is highly quenched in gaseous O_2 at moderately high pressures. We have reported earlier that no $^3S_1$ state positronium pick-off component was observed in liquid oxygen.[10] A recently repeated measurement showed a $(65\pm5)\%$ abundant, 0.49-nsec component and a $(35\pm5)\%$ abundant, ~0.15 nsec component, which are attributed to the annihilation of free positrons and $^1S_0$ state positronium, respectively. A spin-exchange mechanism is assumed to operate rapidly in paramagnetic liquid oxygen to allow an equilibrium statistical distribution of positronium spin states exactly as in free annihilation. Therefore the number of $^3S_1$ to $^1S_0$ positronium state decays observed would be one to 371.

(3) No complex positron-electron-atom bound state which may decay by three-quantum events exists in liquid oxygen.

Based on these assumptions,

$$N_{\rm Al}=aK_1(\theta)/372,$$

$$N_{\rm lox}=aK_1(\theta)(1-p)/372+aK_2(\theta)p/372$$
$$+aK_3(\theta)pf\,371/372,$$

where $N_{\rm Al}$ and $N_{\rm lox}$ are the observed three-quantum events in aluminum and liquid oxygen, respectively; a is the time-integrated number of positrons; $K_1(\theta)$, $K_2(\theta)$, and $K_3(\theta)$ are the

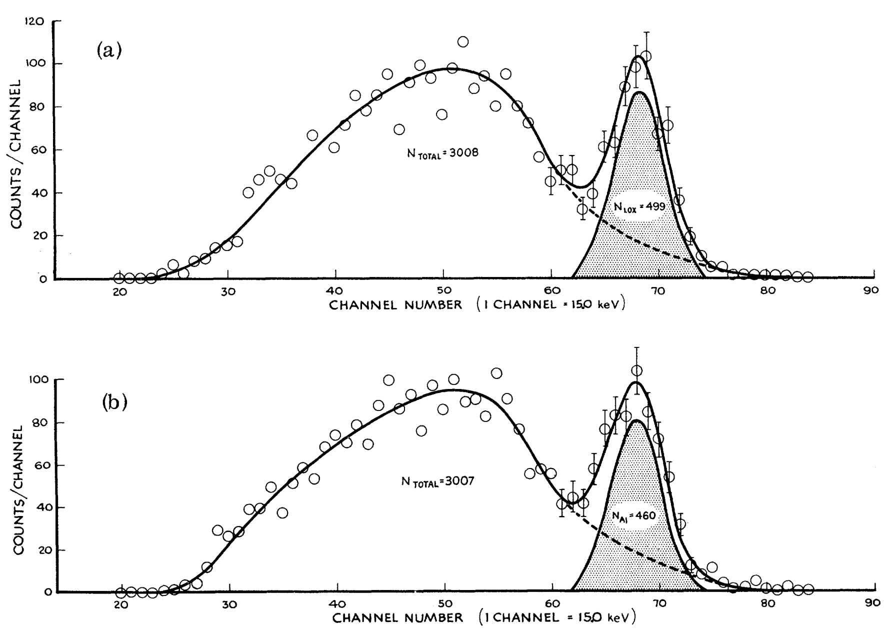

FIG. 1. Summed energy spectrum of three-photon coincidence events in liquid oxygen (a) and aluminum (b). Error bars are counting statistics. Shaded area represents number of true triple-coincidence photons whose total energy (1.02 MeV) is absorbed in three detectors.

triple-coincidence detection efficiencies as a function of angular separation between detectors for free positron annihilation, ${}^3S_1$ positronium decay, and forbidden ${}^1S_0$ positronium decay, respectively; p is the fraction of positrons which forms positronium; and f is the fraction of ${}^1S_0$ state positronium which undergoes three-quantum decay in violation of C invariance. Thus,

$$(N_{\mathrm{lox}}-N_{\mathrm{Al}})/N_{\mathrm{Al}} = -p + pK_2(\theta)/K_1(\theta) + 371pfK_3(\theta)/K_1(\theta).$$

The same average value was observed for $(N_{\mathrm{lox}}-N_{\mathrm{Al}})/N_{\mathrm{Al}}$ in sets of measurements at different angular separations. We assume $K_1(\theta)=K_2(\theta)=K_3(\theta)$, which is reasonable on a physical basis and is not in conflict with the above result.

Six sets of measurements in the described geometry gave values $0.02 \leq (N_{\mathrm{lox}}-N_{\mathrm{Al}})/N_{\mathrm{Al}} \leq 0.10$. The average results gave a value for $f = 0.0005 \pm 0.0003$. One notes that if C-invariance violation exists in the decay of ${}^1S_0$ state positronium, there is no a priori reason why it should not exist in the singlet annihilation. Therefore, technically $(N_{\mathrm{lox}}-N_{\mathrm{Al}})/N_{\mathrm{Al}}$ can be interpreted as a measure of the excess of C-nonconserving decay in the ground-state singlet positronium over similar free singlet decay. From this point of view, one cannot conclude that C conservation was established within the accuracy given but indicates only that C nonconservation, if any, is independent of the radial quantum state.

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IS G PARITY A CONSERVED QUANTUM NUMBER?*

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It is well known that strongly interacting particle systems which have zero strangeness (S) and baryon number (B) are approximate eigenstates of the operator[1] $G = C\exp(i\pi I_2)$, where C represents charge conjugation and I_2 is the "y" component of the isospin $\vec{I}$. Such systems (including single-particle states) are eigenstates of G, I^2, and I_3, and the neutral members are also eigenstates of C. The isospin has integer eigenvalues for these systems, and C and G have eigenvalues ± 1 (referred to hereafter simply as $\pm$).

The strong interactions are believed to conserve C and to be invariant with respect to rotations in isospin space. This would imply that transitions between such states, which proceed via the strong interactions, should conserve G, since the operator G performs a 180° rotation about the I_2 axis followed by the operation C.

If we take a completely experimental approach to this question, however, there does not seem to be any clear-cut measure of the extent to which G is conserved, at least when considered in the following spirit. We assume that $I^2 = I_1^2 + I_2^2 + I_3^2$ and C are conserved (along with total angular momentum and parity) and that all eigenstates of I^2, I_3, C, and G are constructed in the usual manner such that the familiar relationship

$$G = C(-1)^I \tag{1}$$

is valid.

There is, in fact, ample evidence that I^2 is conserved for these systems, as evidenced by the nonoccurrence of the decays $\omega^0 \to \pi^+ + \pi^-$, $\varphi \to \pi^+ + \pi^-$, $\eta'(959) \to 3\pi$, and $A_2^{\pm} \to \pi^+ + \pi^0$. The conservation of I_3, moreover, follows from conservation of charge (Q), since $Q = I_3$ for