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[1]W. Braunschweig *et al.*, Phys. Lett. 57B, 407 (1975).

[2]We use χ as a generic name for new states which are radiatively coupled to ψ particles, reserving the name P_c, suggested by W. Braunschweig *et al.*, for the state which has been identified to have a major decay mode into $\gamma\psi(3095)$ (see Ref. 1). There is currently a twofold ambiguity in the determination of the P_c mass (3.52 or 3.26 GeV/c^2). The 3.53 GeV/c^2 state found here may or may not be the same as P_c.

[3]C. G. Callan *et al.*, Phys. Rev. Lett. 34, 52 (1975); T. Appelquist *et al.*, Phys. Rev. Lett. 34, 365 (1975); E. Eichten *et al.*, Phys. Rev. Lett. 34, 369 (1975); B. J. Harrington *et al.*, Phys. Rev. Lett. 34, 706 (1975); O. W. Greenberg, University of Maryland Technical Report No. 76-012, 1975 (unpublished); also see O. W. Greenberg, University of Maryland Technical Report No. 75-064, 1975 (unpublished), and references therein.

[4]J.-E. Augustin *et al.*, Phys. Rev. Lett. 34, 233 (1975).

[5]G. S. Abrams *et al.*, Phys. Rev. Lett. 34, 1181 (1975); A. M. Boyarski *et al.*, Phys. Rev. Lett. 34, 1357 (1975); V. Lüth *et al.*, SLAC Report No. SLAC-PUB-1599, 1975 (unpublished), and Lawrence Berkeley Laboratory Report No. LBL-3897, 1975 (unpublished).

[6]In this region, the resolution of the square of the missing mass is approximately proportional to the missing energy. Hence the resolution shown for a missing π^0 is much broader in Fig. 2(c) than in Fig. 2(a).

[7]For the reasons discussed in Ref. 6 the reliability of separation of γ's from π^0's is somewhat less at 3.41 than at 3.53 GeV/c^2. However there is an additional argument to show that we are observing $\psi(3864)\rightarrow\gamma\chi(3410)$ rather than $\psi(3684)\rightarrow\pi^0\chi(3410)$. If the latter were to proceed through an interaction which conserves isospin, then the decays $\psi(3684)\rightarrow\pi^+\chi^-$ and $\pi^-\chi^+$ would occur at an equal rate. They are not observed at the level of 0.7 of the expected rate.

[8]From the absence of events in this region we can set upper limits on the branching fraction for the decays $\psi(3684)\rightarrow\pi^+\pi^-$ and $\psi(3684)\rightarrow K^+K^-$ at 1.9×10^{-4} and 2.3×10^{-4}, respectively, at the 90% confidence level.

[9]V. Lüth *et al.*, SLAC Report No. SLAC-PUB-1617, 1975 (unpublished), and Lawrence Berkeley Laboratory Report No. LBL-4211, 1975 (unpublished).

Search for Structure in the γ-Ray Spectra from $\bar{p}d$ and $\bar{p}p$ Annihilations at Rest*†

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The γ-ray spectra from annihilations at rest have been measured with a 10-in.$\times$10-in.-diam NaI(Tl) detector. The resolution of the system was ~15% for γ-ray energies between 50 and 200 MeV. No clear evidence is found for monoenergetic γ rays with intensities greater than 1 per 30 annihilations.

The possibility of the existence of bound states of the nucleon-antinucleon system has been discussed by many authors.[1] Strong attractive forces between the nucleon and antinucleon could result in binding of several hundred MeV. Such states are expected to be short lived because of the annihilation process; however, the theoretical studies suggest that the widths may be less than several MeV for selected states. Thus "capture γ rays" or interstate γ transitions might compete with annihilation.[2]

In a recent publication,[3] the possible observation of such γ-ray transitions was reported. An incident beam of antiprotons was stopped in a deuterium bubble chamber. Approximately one thousand γ rays from annihilation events, producing pairs in the chamber, were observed and the energy spectrum measured. The observed rate of γ rays was about 25% in excess of that expected from π^0 decay, assuming charge independence in the annihilation process. Furthermore, the data suggested that the spectrum of this excess could be in the form of several narrow lines with energies between 80 and 300 MeV and intensities as large as 3% of the total. There was also some indication that certain lines could be enhanced above the π^0 decay background when the γ-ray events were correlated with the charged-pion multiplicity of the annihilation.

We have therefore undertaken an experiment to detect the γ-ray spectra with a NaI detector in an experiment with high efficiency and good statistics. A 750-MeV/c electrostatically separated $\bar{p}$ beam from the internal target station of the Brookhaven National Laboratory's alternating-gradient synchrotron (AGS) was degraded and stopped in a vessel containing either liquid hydrogen or liquid deuterium. The target was surrounded on four sides by eight scintillation counters, which were used to determine the approximate charged-pion multiplicity of each event. Standard techniques were used to generate an electronic signal for each $\bar{p}$ stopped in the target. Typical counting rates of 300 stopped $\bar{p}$'s per AGS pulse were obtained, with negligible contamination from other particles. The γ rays were detected at 90° to the incident beam by a 10-in.-long×10-in.-diam NaI(Tl) crystal[4] almost completely surrounded by a 4-in. shield of plastic scintillator. The plastic was used to improve the detector resolution by detecting radiation (e.g., bremsstrahlung) escaping from the NaI. The entire assembly was contained in a lead shield with a 6.8-in. aperture, in front of which was a scintillation counter, C, used to determine if a charged particle initiated the event in the NaI. Pulse-height spectra for events in the NaI in coincidence with a $\bar{p}$ signal were stored in a 4096-channel pulse-height analyzer. Neutral-particle–induced pulses (C not triggered) were routed into one of seven groups, according to the number of multiplicity counters triggered (0, 1, ..., 5, ≥6); charged-particle–induced pulses (C triggered) were routed into a separate group. Each of these eight groups was divided into four subgroups according to the pulse height in the plastic shield. Thus 32 separate 128-channel spectra were simultaneously stored, with a dispersion of approximately 4 MeV/channel. Further details of the experimental setup have been presented elsewhere.[5]

During the experiment, approximately 475 000 γ-ray events from hydrogen and 573 000 from deuterium were accumulated. The stability of the energy calibration was continously monitored by observing the position of the peak at ~130 MeV produced by charged particles traversing the crystal. The detector resolution and energy calibration were periodically checked by observing γ rays from a π^- beam stopping in the target.

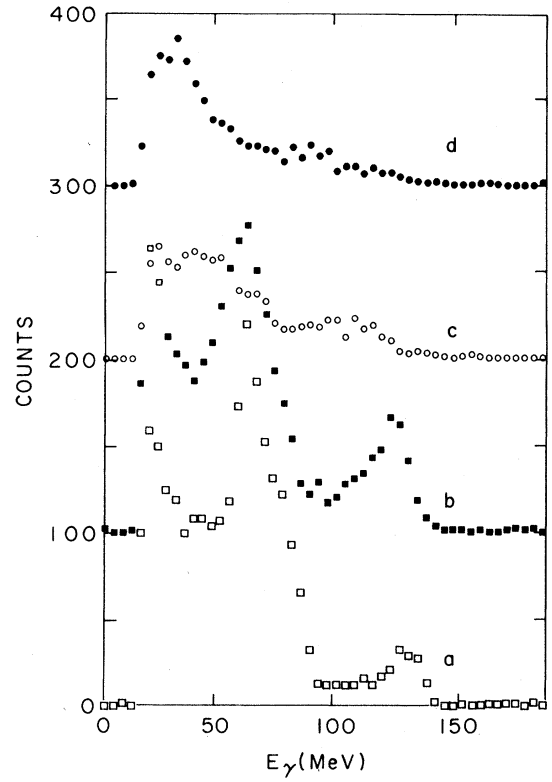

FIG. 1. γ rays from π^-p at rest for the four different shield levels E_s. a, $0 \le E_s \le 1.1$ MeV; b, $1.1 \le E_s \le 4.4$; c, $4.4 \le E_s \le 7.6$; and d, $E_s \le 7.6$. For clarity, each spectrum has been displaced upward by 100 counts relative to the next lower spectrum.

Typical spectra from stopping π^- in hydrogen are shown in Fig. 1 for each of the four levels in the plastic shield. These spectra exhibit the line from $\pi^- + p \to n + \gamma$ at 129 MeV in addition to the broad distribution from π^0 decay from the $\pi^- + p \to n + \pi^0$ channel. It is seen that the resolution in the 130-MeV region is about 15% full width at half-maximum for the lowest two shield levels. The shift in the position and variation of intensity of the 129-MeV peak with shield level as well as the low-energy tail are due to leakage of energy out of the NaI.

Figure 2(a) shows the $\bar{p}d$ γ-ray spectra for the same shield levels as in Fig. 1, summed over all multiplicities. None of these or the corresponding $\bar{p}p$ spectra show significant line structure. Studies of spectra sorted by different multiplicities also reveal no intense line structure. The general shape of the observed continuum is significantly affected by leakage of energy out of the scintillator and thus changes depending on the shield level . The sharp rise at low energies

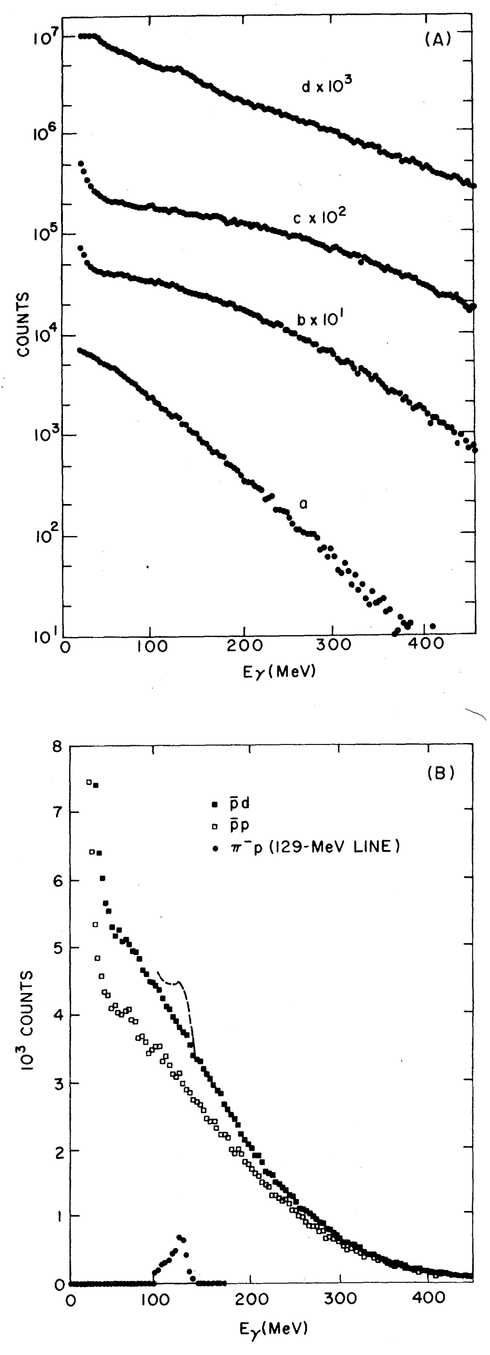

FIG. 2. (a) γ rays from $\bar{p}d$ summed over all multiplicities, where the spectra labels a–d have the same meaning as in Fig. 1. For clarity, each spectrum has been displaced upward by a factor of 10 relative to the next lower spectrum. The corresponding $\bar{p}p$ spectra are virtually identical to these. (b) Linear plot of γ rays from $\bar{p}d$ and $\bar{p}p$ for the second shield level only. The dashed line is the result of adding a 129-MeV γ ray of 1% intensity to the $\bar{p}d$ spectrum, as discussed in the text. For reference, the 129-MeV γ ray is also shown.

can be attributed to this effect and to the scattering of γ rays from the collimator surfaces. Since the probability of leakage increases with γ-ray energy, the spectrum with the lowest shield level (corresponding to less than 1.1 MeV deposited in the plastic) drops off sharply with increasing energy. As the shield level increases, more and more high-energy events with deteriorating resolution are accepted, and the spectra tend to flatten out. These effects have been studied and are consistent with the changes in the shape of the π^-p spectrum as a function of shield level shown in Fig. 1. Checks of the absorption of the spectrum by thin absorbers indicate that the spectra are not significantly contaminated by neutrons. Furthermore, the number of events not correlated in time with a $\bar{p}$ incident on the target were shown to be negligible. Details of these studies have been discussed in Ref. 5.

The spectra from both $\bar{p}p$ and $\bar{p}d$ are shown in Fig. 2(b) for the second shield level only. In order to demonstrate the sensitivity of the experiment, we have artificially constructed the spectrum shown as the dashed line in Fig. 2(b), which is the sum of the $\bar{p}d$ spectrum plus the 129-MeV γ ray observed in π^-p. The intensity of the 129-MeV line has been normalized such that the total counts in the peak summed over all four shield levels equals 1% of the total $\bar{p}d$ continuum. The resulting spectrum is shown for the second shield level only. A line of 1% intensity is clearly distinguishable. The absence of a calibration line above 130 MeV makes it difficult to be certain of the NaI response and line shape at energies much above the pion mass. It should further be noted that spectra associated with individual multiplicities show line structure at the level of a few tenths of a percent intensity. These structures appear at several energies below 200 MeV. However, in general they do not exhibit the signature of intensity variation with shield level expected from the calibration data for γ rays from the target. It might be assumed that they result from secondary interactions of annihilation products in the shield and collimator materials. In addition, the secondary process of production of γ rays from the stopping of low-momentum annihilation π^-'s in the target should produce the π^-p spectrum at the level of a few tenths of a percent. In fact, a hint of this can be seen in the spectra of Fig. 2(b). Thus the sensitivity of the experiment to annihilation γ rays becomes limited at the few tenths of a percent level.

Thus we conclude that the sharp line structure suggested in Ref. 3 is not observed in the present experiment. We conservatively set a limit on the intensity of such structure at 1% of the continuum for lines between 50 and 200 MeV. Since on the average there are three γ rays emitted per $\bar{p}$ annihilation,[3] our upper limit corresponds to an intensity of less than one γ ray of discrete energy per thirty annihilations. This result is consistent with theoretical predictions[2] of very small γ-ray branching ratios in the $N\bar{N}$ system.

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Phenomenology of Goldstone Neutrinos*

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The hypothesis that the physical neutrino is a Goldstone particle associated with spontaneously broken supersymmetry is studied with emphasis on the ensuing low-energy theorems. A picture of low-energy neutrino phenomenology is found which is attractive for neutral-current processes, but is in strong disagreement with experimental end-of-lepton-spectrum behavior in β decays.

Supersymmetric field theories are an elegant theoretical development,[1] but unfortunately no clear physical application is yet apparent. Since there are no degeneracies in mass between bosons and fermions in nature (expect between photon and neutrino, which is considered below), the supersymmetry, if applicable at all, must be broken. If the breakdown is spontaneous, the Goldstone theorem[2] requires the existence of a massless chiral spin-$\frac{1}{2}$ particle, and it is an attractive hypothesis[3] that the physical neutrino is this particle.

The present theoretical status of this hypothesis is that a general proof[4] of the Goldstone theorem in the case of supersymmetry has been given, and Lagrangian models of spontaneously broken supersymmetry[5-7] have been constructed. These models are generalizations of the original Wess-Zumino-Iliopoulos Lagrangian and of Lagrangian models in which supersymmetry is combined with either Abelian[8] or non-Abelian[9] gauge invariance. The most realistic model, due to Fayet,[6] is a unified description of the weak and electromagnetic interactions of an electron, its neutrino, and other heavy particles. Present models do not naturally describe two neutrinos (ν_e and ν_μ) but the general framework may be flexible enough to accomodate them.

It is to be expected that low-energy theorems[10] of the Nambu-Adler and Adler-Weisberger type apply to Goldstone neutrinos and that the resulting suppression of low-energy neutrino processes