bilities, however, might enable the lower mass limit to be pushed past the 22-MeV figure. There is a probable (0^+, $T=0$) structure[10] at approximately 24.0 MeV in ^{8}Be which could be reached, e.g., by $^6\text{Li}+d$, $Q=22.28$ MeV.[10] Whether or not the resonance parameters are such as to permit a feasible scalar-particle search is not clear. There may well be suitable 0^+ structures in the energy-level scheme of ^{12}C though the relevant information is not yet available. For instance structures[11] at 26.9 MeV and 28.46 MeV in the ^{12}C nucleus are suggestive of 0^+ though certainly not established. Use of the reaction $^9\text{Be}+{}^3\text{He}$, $Q=26.28$ MeV,[11] would seem to provide a reasonable approach provided a suitable state in ^{12}C can be found. (It should be noted that any J^π to J^π transition might be a suitable candidate since particle decay widths will dominate for the decay of such high-lying states anyway.) Finally it should be noted that ^{16}O might have suitable high-lying 0^+ states which could be reached, for instance, with the $^{13}\text{C}+{}^3\text{He}$ reaction, $Q=22.79$ MeV,[12] though the first two possibilities mentioned above would seem more likely to be useful.

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Observation of Charge-Independence-Violating Effects in $\bar{p}d$ Annihilations at Rest*

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For $\bar{p}d$ annihilations at rest, charge independence and energy conservation imply that the average energy going to charged pions is $\langle E_\pm\rangle = 1241\pm 2$ MeV per annihilation. Experimentally this number is found to be 1169 ± 10 MeV after corrections for events with invisible $K^0\bar{K}^0$. This discrepancy of 72 ± 10 MeV cannot be accounted for by the known η and ω production which is estimated to contribute $\sim 14\pm 3$ MeV.

Studies of antiproton annihilations in hydrogen and deuterium at rest and low energies have revealed many unusual phenomena suggestive of narrow $\bar{N}N$ bound and resonant states.[1] If such states do exist electromagnetic effects might be unusually large, leading to a measurable violation of charge independence in these reactions. A test of charge independence in $\bar{N}N$ reactions, apart from testing the general principle, would also throw some light on the nature of these narrow bound states. Charge independence leads to many relations for $\bar{p}p$ and $\bar{p}n$ annihilations[2] but for $\bar{p}d$ the following useful equality exists[3]:

$$N_+(\omega)+N_-(\omega)=2N_0(\omega), \tag{1}$$

where N_+, N_-, and N_0 are the numbers of—or cross sections for—π^+, π^-, and π^0 production. This holds at any pion energy-momentum,[4] direction, and final state (e.g., 4π, $3\pi\bar{K}K$, etc.). Multiplying (1) by ω and integrating, we get the following relation among the total average energies taken by π^+, π^-, and π^0:

$$\langle E_+\rangle+\langle E_-\rangle=2\langle E_0\rangle. \tag{2}$$

Making use of energy conservation in annihilations

$$\bar{p}+d\rightarrow\text{pions}+\text{nucleon}, \tag{3}$$

we find that

$$\langle E_\pm{}^{\rm CI}\rangle=\tfrac{2}{3}\langle E_A\rangle \tag{4}$$

for annihilation into pions. Of course, $\langle E_0{}^{\rm CI}\rangle=\frac{1}{3}\langle E_A\rangle$, where $\langle E_A\rangle$ is the energy available to all pions. In this experiment, we will measure $\langle E_\pm\rangle$ and $\langle E_A\rangle$ and check the charge-independence prediction (4).

We analyzed annihilations from an exposure of the Brookhaven National Laboratory 30-in. deuterium bubble chamber (30-in.-diam, 13-in.-depth cylinder, magnetic field and optical axes parallel to the cylinder axis) to a pure antiproton beam brought to rest in the central region of the chamber. About 2000 pictures were scanned and only those with five or fewer antiprotons entering the fiducial region were accepted; all charged tracks of the annihilation events were measured and reconstrcuted by using the CERN program THRESH, modified to include the geometry calculation of the CERN program GRIND. Physicists—in pairs—compared the THRESH output with the events on the pictures with the following emphasis: not to miss any events; to identify p, $K^\pm$, K^0, and Dalitz pairs; to search for $\bar{n}$ stars; and to note the stopping $\pi^\pm$ and check that all tracks were measured. After a further fiducial cut defined by the vertex coordinates the events shown in Table I, except for 131 kaons and seven "Zoo," were obtained totally. The Zoo events could not satisfy the charge or baryon-number conservation for annihilations in deuterium (e.g., four of them had more than one proton in the final state). These events are too few to affect our conclusions and will not be considered further.

TABLE I. $\bar{p}+d\rightarrow$ pions + nucleons. $N_{\pi^\pm}$, number of prongs ($\pi^\pm$); N^T, total number of events; N^R, those with at least one track unmeasurable; N^G, $N^{\rm INT}$, well measured, interacting (< 12 cm) $\pi^\pm$, respectively; E^G, energy (GeV) of N^G; $\langle\omega^{\rm INT}\rangle$, average energy of interacting pions obtained from πd cross sections and observed $\pi^\pm$ spectra; $E^{\rm INT}=N^{\rm INT}\langle\omega^{\rm INT}\rangle$ and $E^T=E^G+E^{\rm INT}$; $\langle\omega_\pm\rangle=E^T/(N^G+N^{\rm INT})$; and $E_\pm=\langle\omega_\pm\rangle N^T N_{\pi^\pm}$, total energy in GeV of all charged pions.

	EVENTS		$\pi^\pm$ WITH DIP < 45°							
$N_{\pi^\pm}$	N^T	N^R	N^G	$N^{\rm INT}$	E^G	$\langle\omega^{\rm INT}\rangle$	$E^{\rm INT}$	E^T	$\langle\omega_\pm\rangle$	$E_\pm$
0	81 ± 6									0
1	260	6	182	9	89	.391	4	92	.482	125
2	805	19	1067	45	473	.401	18	491	.441	710
3	836	26	1639	72	657	.373	27	684	.400	1003
4	855	38	2232	139	811	.355	49	861	.363	1242
5	313	22	989	59	327	.337	20	347	.331	518
6	65	5	245	15	71	.319	5	76	.292	114
7	8	3	25	1	7	.319	0	8	.288	16
	3223 ± 6	119	6379	340	2435		123			3728

Prong frequencies (Table I) are in good agreement with other data except for zero prongs[5] which have to be corrected for charge exchange. Our correction is based on the observed four $\bar{n}$ stars (two or more low-ionization prongs) and a lower-limit estimate of 30% for producing such stars. Independent tests support this result: (a) An experiment with small in-flight contamination gives the same zero-prong frequency, and (b) observations of γ frequencies decrease smoothly with increasing prong multiplicity. The strange-particle frequency after correcting for invisible $\bar{K}^0K^0$ (30 ± 6 events) is $(4.9\pm0.4)\times10^{-2}$ and is in agreement with other studies.[5]

The energy available to pions ($\langle E_A\rangle$) is estimated by accounting for the contribution of the in-flight events and for the energy taken by the "spectator" nucleon. Using $\bar{p}d$ one-constraint cross sections (known for momenta > 260 MeV/c) and extrapolating them smoothly ($\propto 1/P$), we find that on the average + 7 MeV is contributed to the total energy per event by the in-flight annihilations. The well-known[1] proton spectra yield 21 ± 2 MeV per event to the proton. With the reasonable assumption, supported also from the total energy of the channels without π^0, that the neutron spectator has the same spectrum, we find $\langle E_A\rangle=1862\pm2$ MeV. This result is in agreement

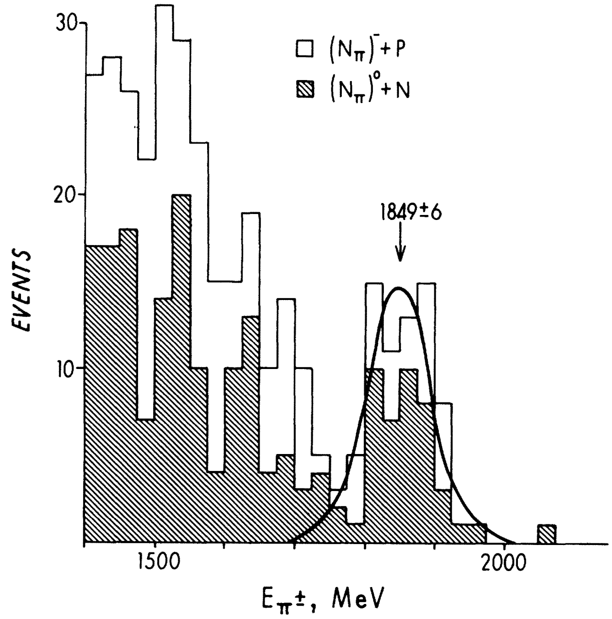

FIG. 1. Event distribution as a function of the total energy (per event) for well measured $\pi^\pm$.

with the well-defined peaks in Fig. 1 which correspond to annihilations into charged pions only, with a proton or a neutron in the final state. According to (4),

$$\langle E_\pm^{\mathrm{CI}} \rangle = 1241 \pm 2 \text{ MeV}. \quad (4')$$

The momentum errors increase with dip angle and decrease with track length. Since all directions for stopping antiprotons are equivalent,[6] we used the momenta of $\pi^\pm$ with dip $< 45°$ for the determination of $\langle E_\pm \rangle$. The geometry is such that pions with momentum > 70 MeV/c traverse more than 12 cm (with average length of ~30 cm) or interact. Pions with momentum < 70 MeV/c stop. For noninteracting pions $\delta p/p \simeq \pm 2\%$.

Table I shows the relevant data and corrections for event losses and interacting pions. We thus obtain a total energy 3728 GeV released by the 3223 ± 6 events to the charged pions. Consequently,

$$\langle E_\pm \rangle = 1157 \pm 10 \text{ MeV}, \quad (5)$$

which is 84 ± 10 MeV lower than expected from charge independence, Eq. (4′). The error is statistical and was estimated from the spread in $\langle E_\pm \rangle$ of equivalent Monte Carlo experiments generated using as *a priori* probability the observed $E_\pm$ distribution. It is of interest to note that this charged energy is lower by 68 and 97 MeV for $\bar{p}n$ and $\bar{p}p$ annihilations.

The following systematic biases were considered: (a) contamination from Dalitz pairs, (b) proton-K^+ ambiguities, and (c) $\bar{K}^0K^0$ events with invisible decay modes. We found 46 Dalitz pairs and six ambiguities which were classified as protons. These biases increase the effect and are estimated to be contributing $\lesssim 5$ MeV. From the observed K_S and K_SK_S events, we estimate that our sample of pionic annihilations contains 30 ± 6 events with invisible $\bar{K}^0K^0$ while their average energy is 1260 ± 10 MeV found from other studies[7] involving large samples of K_SK_S pairs. This results to a correction of 12 ± 2 MeV and thus

$$\langle E_\pm^{\mathrm{CI}} \rangle - \langle E_\pm \rangle = 72 \pm 10 \text{ MeV}; \quad (5')$$

that is, an excess of 72 ± 10 MeV in the energy of the neutrals (π^0, γ) is observed above what is expected, 621 ± 1 MeV, from charge independence.

In order to assess the significance of the effect seen, the isospin-nonconserving contributions of the η and ω (η' contribution is negligible) electromagnetic decay modes should be considered. The energy taken by the γ's in these decays will contribute to the excess of neutral energy observed. For estimating the magnitude of these contributions one needs (a) the average energy of η and ω, (b) the fraction of this energy that goes to γ, and (c) the production frequencies of η (f_η) and ω (f_ω) in $\bar{p}d$ at rest.

The average energies can be inferred from the observation that inclusive momentum spectra are particle independent,[7,1b] yielding 750 MeV for $\langle \omega_\eta \rangle$ and 900 MeV for $\langle \omega_\omega \rangle$. By using the decay branching fractions and the assumption that in a specific charged decay mode the average energies of $\pi^\pm$, π^0, and γ are the same, one gets $\langle E_\gamma \rangle = 0.474 \langle \omega_\eta \rangle$ and $\langle E_\gamma \rangle = 0.057 \langle \omega_\omega \rangle$ for η and ω, respectively. Consequently, they contribute towards the effect $356 f_\eta + 51 f_\omega$ MeV.

The production frequencies in deuterium (f_η, f_ω) are not known inclusively but are known (Table II) in many multipion final states from $\bar{p}p$ and $\bar{p}n$, thus making possible reasonably safe estimates. Note that the observed effect would be accounted for by 20% η or 141% ω production frequencies which are an order of magnitude higher than the total observed frequencies. In the estimate of the η and ω frequencies in deuterium (Table II) from those observed from $\bar{p}p$ and $\bar{p}n$ (associated with low-momentum protons) annihilations, the following have to be kept in mind:
(a) The limits on the three-body production are based on the observed $\pi^+\pi^-(\eta, \omega)$ frequency for

TABLE II. Production of η and ω in annihilations at rest.

$X=\eta, \omega$	Final State	Resonant Intermediate State	% of all ($\bar{N}N$) Annihilations[a,b]	Phase Space Ratio[c,d]	% of Resonance Production in Final State	% of η Production to all $\bar{p}d$ Annihil.	% of ω Production to all $\bar{p}d$ Annihil.
πX	$2\pi^-\pi^+\pi^0$	$\pi^-\eta$	$< .02$	.015	.0006 ($\pm$25%)	$< .01$	$.24 \pm .04$
		$\pi^-\omega$	$.33 \pm .05$	.15	$.02 \pm .003$		
	4γ (5γ)	$\pi^0\eta^0$	.02 ($\pm$25%)				
		$\pi^0\omega^0$	.9 ($\pm$50%)				
$2\pi X$	$2\pi^-2\pi^+\pi^0$	$\pi^-\pi^+\eta$	$1.3 \pm .1$	.05	$.02 \pm .002$	$1.1 - 1.9$ $\pm.1$ $\pm.1$	$4.3 - 7.1$ $\pm.2$ $\pm.3$
		$\pi^-\pi^+\omega$	$5.0 \pm .2$	.5	$.23 \pm .01$		
	6γ	$2\pi^0\eta$	.9 ($\pm$30%)				
$3\pi X$	$3\pi^-2\pi^+\pi^0$	$2\pi^-\pi^+\eta$	$< .3$	.1	$< .04$	$\lesssim .8$	$5.8 - 11$ $\pm.7$ ±1
		$2\pi^-\pi^+\omega$	$6.3 \pm .8$	.1	$.88 \pm .09$		
$4\pi X$	$3\pi^-3\pi^+\pi^0$	$2\pi^-2\pi^+\eta$	$.12 \pm .05$	.5	$.02 \pm .01$	$.4 \pm .3$	4 ± 1
		$2\pi^-2\pi^+\omega$	$1.1 \pm .3$	.9	$.6 \pm .2$		

[a]From (a) Ref. 1a; (b) review by L. Montanet, in *Proceedings of the International Conference on Elementary Particles, Lund, Sweden, 1969,* edited by G. von Dardel (Berlingska Boktryckeriet, Lund, Sweden, 1970); (c) S. Devons *et al.*, Phys. Lett. 47B, 271 (1973), on $2\pi^0\eta^0$; (d) J. Skelly, Ph. D. dissertation, Syracuse University, 1972 (unpublished), on $\pi^0\eta^0$ and $\pi^0\omega^0$; (e) P. Haggerty, Ph. D. dissertation, Syracuse University, 1969 (unpublished), on $2\pi^-\pi^+\omega$; and (f) A. Bettini *et al.*, Nuovo Cimento 47A, 642 (1967), on $\bar{p}n$ final states.

[b]For all decay modes.

[c]Phase space at η, ω mass over maximum.

[d]$\eta, \omega \to \pi^+\pi^-\pi^0$.

$I=0$ or 1. Analyses of the $\pi^+\pi^-\eta$ Dalitz plot[8] favor equal mixture of $I=0, 1$ while the $2\pi^0\eta$ frequency suggests pure $I=0$. (b) From the observation of the pure $I=1$ $2\pi^-\pi^+(\eta, \omega)$ and for $I(\pi^+\pi^-) = 0, 1$, $f_{3\pi\eta} < 0.3\times10^{-2}$ and $(5.8\pm0.7)\times10^{-2} < f_{3\pi\omega} < (7.2\pm0.9)\times10^{-2}$. In addition, the $I=0$ $\pi^+\pi^-\pi^0(\eta, \omega)$ have to be inferred, and this is the only significant uncertainty in our estimates. We appeal here, first, to general patterns of resonance production indicated in Table II for η and ω production (the same is also true of ρ and f production): The resonance production is proportional to phase space, namely, their production is small at the tails and large at the maxima of phase space. Secondly, it is difficult to envision mechanisms in multiple-pion final states for which the isospin will provide strong constraints on production from $I=0$ or 1. In fact, a statistical bootstrap model[9] explicitly disregarding isospin conservation gives the best (excellent) agreement so far with all observed branching ratios. It might be of interest to note that this model predicts a $\bar{p}p \to 2\pi^+2\pi^-2\pi^0$ frequency from $I=0$ of 0.08 which for deuterium is 0.046, and it will require abnormal η (~100%) and ω (~zero) production in this channel in order to come close to accounting for the effect. The same fraction of η and ω production as observed from $I=1$ has been used for our estimate. (c) The $3\pi^-3\pi^+\pi^0$ is a mixture of $I=0, 1$ and the $2\pi^-2\pi^+(\eta, \omega)$ channel has "maximum charge complexity" [contrast to $4\pi^0(\eta, \omega)$] and all internal states contribute. Our estimate, which is likely an overestimate, assumes the same η and ω production ratios in all 6π charged states as in $3\pi^-3\pi^+\pi^0$ with 6π frequencies given by the statistical bootstrap model.[9]

It is likely that we overestimate the η and ω production in deuterium by about 20–30%. We have applied a linear superposition of $\bar{p}p$ and $\bar{p}n$ frequencies and this is not quite applicable because of the tails of the "spectators" representing about $\frac{1}{4}$ of all events. Resonance production (viz. ρ, ω) decreases with increasing spectator momentum to the extent that in the tail ($\gtrsim 250$ MeV/c) a suppression by a factor of 3 is observed.[1b] Combining our η and ω production estimates we obtain $(1.1\pm1)\times10^{-2} \leq f_\eta \leq (2.7\pm0.1)\times10^{-2}$ and $(10.3 \pm 0.7)\times10^{-2} \leq f_\omega \leq (18\pm1)\times10^{-2}$, which yield a contribution of 14 ± 3 MeV to the observed excess in neutral energy.

We conclude that in $\bar{p}d$ pionic annihilations at rest the neutral energy observed experimentally exceeds by 72 ± 10 MeV the value 621 ± 1 MeV predicted by charge-independence considerations. An estimate of the η and ω electromagnetic decay contributions reduces this number to 58 ± 11 MeV. This still corresponds to an excess of 9.3% over the value expected for the neutral energy from charge independence, and is much higher than electromagnetic mass splitting in isospin multiplets which is typically of the order of $<1\%$.

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Observation of Excessive and Direct γ Production in $\bar{p}d$ Annihilations at Rest*†

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The charge-independence-violating effects observed in the previous paper are caused by the production of 0.73 ± 0.08 γ per annihilation above what is expected, 3.04 ± 0.02, from charge independence. The γ-energy spectrum extends over the γ spectrum generated from π^0. The spectra associated with specific topologies show peaks which are indicative of electromagnetic transitions between $\bar{p}N$ bound states or states of the cosmion (C).

Following our observations[1,2] of charge-independence-violating effects in $\bar{p}d$ annihilations at rest we have undertaken a study of the γ-energy spectra. Our objectives were twofold: (1) to identify the source of the excess in the energy of the neutrals, and (2) to look for the electromagnetic transitions

$$\bar{p} + d \to (N\bar{N})^* + N \qquad (1a)$$
$$\hookrightarrow (N\bar{N})^{**} + \gamma \qquad (1b)$$

which would produce peaks in the γ-energy spectra. Several direct and indirect observations[3] have strongly suggested the existence of narrow bound and resonance $N\bar{N}$ states and have been the motivating force for these searches for electromagnetic effects.

To this end we have double scanned the same[2] $\bar{p}d$ bubble chamber film, searching for e^+e^- pairs from γ conversions anywhere in the chamber. We found that ~95% of all such pairs point to an annihilation vertex. Comparison of the two scans yields an overall scanning efficiency of ~93% and 2317 events were found in 12 500 frames representing 5% of the available film. After geometrical reconstruction, in order to improve the resolution, only those γ's whose vertices are ~10 cm away from the chamber walls and have a dip angle $<45°$ have been accepted. After two measurements 96% of all events were reconstructed. The momentum of the pairs was found pointing (all with $<3°$ and 50% of them $<1°$) to an annihilation vertex. The average energy resolution ($\Delta E/E$) for the γ energy, as determined from the e^+e^- energies, is ~±5% with $|\Delta E/E| < 10\%$ for 90% of the γ's. (Higher percentage errors are frequently associated with low-energy γ's.)

The observed γ average energy is found to be 210 ± 4 MeV. The scanning efficiency was found to be independent of energy. After taking into account the energy dependence for pair production