point energy of 11.2±0.6 MeV for the F^{22} β rays. Unfortunately, the counting rate of β's gated by γ rays was so low that it was not possible to determine from the data whether the β spectrum in coincidence with γ rays has a different end point than the ungated spectrum. All that can be said at the present is that the observations are consistent with the two spectra having the same end point; the same end point for both spectra implies that no β-ray transitions directly to the ground state of Ne^{22} occur.

Measurements of the half-life of F^{22} were made by observing the number of β rays emitted from F^{22} (with and without a γ-ray coincidence requirement) as a function of time. The observed half-life is 4.0±0.4 seconds.

A proposed decay scheme of F^{22} is shown in Fig. 2. The levels of Ne^{22} with their spin and parity assignments are those reported by other workers.[2-3] The branching ratios of 0.67 and 0.33 to the 3.35- and 1.28-MeV states of Ne^{22} are those obtained from the relative intensities of the 1.28- and 2.07-MeV γ rays. Other work indicates that the γ decay of the 3.35-MeV state goes essentially entirely through the 1.28 state; the lack of a 3.35-MeV γ ray in our observed γ-ray spectrum is in agreement with this decay. No β branch to the ground state is shown on the decay diagram; as indicated previously, the β-spectrum observations are consistent with this decay but are not precise enough to definitely confirm it. The logft values for the decays of the 3.35- and 1.28-MeV states were calculated to be 5.9 and 6.4, respectively; these values are close to the upper end of the range for allowed transitions. If both these decays are by allowed transitions, the ground state of F^{22} must have a spin-parity assignment of 3^+; it could not then decay to the 0^+ ground state of Ne^{22} by an allowed transition. From the observed β-ray end-point energy and the proposed decay scheme, the F^{22}–Ne^{22} mass difference is 12.5±0.6 MeV.

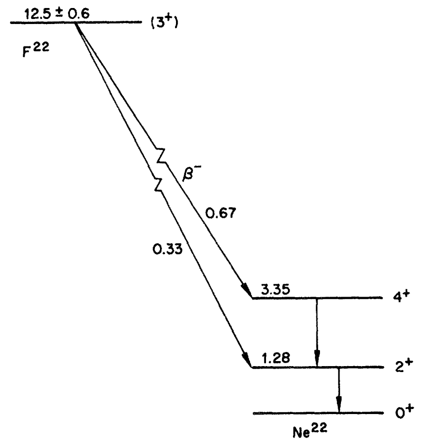

FIG. 2. Proposed decay scheme of F^{22}.

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SEARCH FOR C-INVARIANCE VIOLATION IN η(958 MeV) AND η(549 MeV) DECAYS*

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There is now much interest in the possibility of C (charge conjugation) noninvariance in strong or electromagnetic interactions, which is due to the existence of C-nonconserving but parity-conserving interactions.[1,2] The C-invariance violation is a few percent at most for the strong interactions and can be maximal for the electromagnetic interactions. Such C-nonconserving effects may be found by looking for (1) C-nonconserving decay modes of neutral mesons[3-6] or (2) asymmetries between π^+ and π^- in the three-particle decay modes of these same mesons.[3,4,7] We have looked for such decay modes and asymmetries arising from η(958) and η(549)[8]

produced in the reaction $K^- + p \to \Lambda + \eta(958)$ with subsequent decay $\eta(958) \to \eta(549) + \pi^+ + \pi^-$. No definite evidence for such C-invariance violating effects is observed, although their presence cannot be ruled out. The smallness of the decay of $\eta(549)$ and $\eta(958)$ to $\pi^0 + e^+ + e^-$ is of particular interest. The branching fractions are <0.007 and <0.013, respectively; 0.01 and 0.02, respectively, might be expected.

The $\eta(958)$ mesons are produced in the reaction $K^- + p \to \Lambda + \eta(958)$. About 700 000 pictures of 2.1-, 2.45-, 2.55-, 2.63-, and 2.70-BeV/c K^- mesons incident upon the 72-in. hydrogen bubble chamber have been used. Essentially all of the V-plus-4- or -6-pronged events have been measured, as well as about two-thirds of the V-plus-2-pronged events. All events in which the mass, M_Λ, of the system recoiling against the Λ is in a wide band about 958 MeV $[0.80 \leq M_\Lambda{}^2 \leq 1.04\ (\mathrm{BeV})^2]$ had previously been selected and fitted to the final states $\Lambda\pi^+\pi^-\gamma$ and $\Lambda\eta\pi^+\pi^-$ in addition to the usual hypotheses, as reported previously.[9] A subset of these events was selected for final processing in the search for the possible C-nonconserving decay modes, $\eta(549 \text{ or } 958) \to \pi^0 + e^+ + e^-$ or $(\pi^+ + \pi^-)_{T=0} + e^+ + e^-$, or $\eta(958) \to \eta(549) + e^+ + e^-$. For this search, only events with low momentum transfer to the Λ, $\Delta_{p,\Lambda}{}^2 < 0.5\ (\mathrm{BeV})^2$, were used. The subset was chosen by calculating the missing mass opposite all visible particles, using the electron mass in place of the pion mass for all possible $e^\pm$ combinations among the charged tracks at the production vertex. Those events having a missing mass near 0, π^0, or $\eta(549)$ $[-0.05 \leq \mathrm{MM}^2 \leq 0.4\ (\mathrm{BeV})^2]$ were retained. The original measurements were selected from the measurement-library tapes and reprocessed through geometry and kinematics (PACKAGE) with all the appropriate hypotheses, including electrons. Fits or missing-mass calculations were tried to the following reactions:

$$\begin{aligned}
K^- + p &\to \Lambda + \pi^+ + \pi^- (+\text{neutrals}) \\
&\to \Lambda + e^+ + e^- (+\text{neutrals}) \\
&\to \Lambda + 2\pi^+ + 2\pi^- (+\text{neutrals}) \\
&\to \Lambda + \pi^+ + \pi^- + e^+ + e^- (+\text{neutrals}) \\
&\to \Lambda + 3\pi^+ + 3\pi^- \\
&\to \Lambda + 2\pi^+ + 2\pi^- + e^+ + e^-,
\end{aligned}$$

where intermediate $\eta(549)$ and/or Σ^0 production and decay were included as required. Of approximately 75 000 original V-plus-2- or -4-pronged measurements, approximately 16 000 had $0.80 \leq M_\Lambda{}^2 \leq 1.04\ (\mathrm{BeV})^2$; the final selected subsample used here has about 2500 events.[10] Many electron hypotheses were fitted satisfactorily. Essentially all those hypotheses having a momentum less than about 200 MeV/c for either electron were ruled out on the basis of the visible ionization. No distinction between pions and electrons was possible at higher momenta. We obtained many ambiguous fits between $\Lambda\pi^+\pi^0\pi^-$, $\Lambda\pi^+\pi^-\gamma$, $\Lambda\pi^0 e^+e^-$, and $\Lambda e^+e^-\gamma$ in particular, which presumably are really $\Lambda 3\pi$ or $\Lambda 2\pi\gamma$.[11]

The candidates for the various decay modes are given in Table I. The second column gives the number of events that fit best to the decay listed in the first column, the third column gives the number of unambiguous cases, and the fourth column gives other candidates.[12] The fifth and sixth columns give, respectively, the observed number of definite candidates, and the lowest (three-standard-deviation) upper limit consistent with columns 2 through 4. The seventh column gives the number of such events expected on the basis of the crude theoretical estimates[3,4] that have been made.[13] Finally, the last column gives the upper limit to the branching fractions. Clearly the data are consistent with C invariance, although the observed upper limits are not inconsistent with the theoretical expectations. However, the 0 ± 1 $\eta(549)$ and 0 ± 3 $\eta(958) \to \pi^0 + e^+ + e^-$, taken at face value, are less than the expected 3 and 15, respectively.[14]

No statistically meaningful asymmetries between π^+ and π^- in the decay of $\eta(958) \to \eta(549) + (\pi^+ + \pi^-$ or $\pi^- + \pi^- + \gamma)$ are observed. The relevant numbers are presented in Table II.[15,16] Clearly a sample an order of magnitude larger would be needed before one could expect to see any real effect, if present.

In summary, a search for C-nonconserving decay modes and asymmetries in $\eta(549)$ and $\eta(958)$ decays has been made. No C-invariance violating effects are observed, although the sensitivity of the measurement is such that even a maximal violation in electromagnetism cannot be ruled out. However, as noted above, the $\pi^0 e^+e^-$ decays may be suppressed relative to current crude estimates. Such a suppression might be due to the operation of some approximate quantum number,[17] or the fact that

Table I. C-violating decay modes for $\eta(549)$ and $\eta(958)$.[a]

Mode	Events: Best fit	Events: Unambiguous	Events: Other[b]	Observed events: Definite	Observed events: Upper limit	Expected events[c]	Observed branching fraction[d]
$\eta(549)\to\pi^0+e^++e^-$	0	0	3	0	3	$0.03\times(89\ \eta_C\pi^+\pi^-)=3$	<0.007
$\to\pi^++\pi^-+e^++e^-$	0	0	...	0	3	$0.002\times(89\ \eta_C\pi^+\pi^-)=0$	<0.007
$\eta(958)\to\pi^0+e^++e^-$	3 ± 5^e	0	$\frac{0\pm1}{0.33}$	0	9	$0.1\times(152\ \pi^+\pi^-\gamma)=15$	<0.013
$\to\eta+e^++e^-$ $\{\eta_N$	$\frac{-4\pm3^e}{0.7}$	$\frac{0}{0.7}$	...	0	7	$0.01\times(152\ \pi^+\pi^-\gamma)=2$	<0.011
$\to\eta+e^++e^-$ $\{\eta_C$	$\frac{0}{0.3}$	$\frac{0}{0.3}$	...				
$\to\pi^++\pi^-+e^++e^-$	2	2	...	2^f	6	$0.01\times(152\ \pi^+\pi^-\gamma)=2^f$	<0.006
$\eta(958)\to\rho^0+\pi^0$	...	...	7 ± 6^e	0	25	$\approx0.01\left(\frac{172\ \eta_N\pi^+\pi^-}{0.36\pm0.05}\right)=5^g$	<0.04
$\to\omega^0+\pi^0$	...	...	29 ± 9^e	0	56		<0.08

[a]As determined from events with $0.89\le M_\Lambda{}^2\le0.95$ (BeV)^2 and $\Delta_{p^2,\Lambda}\le0.5$ (BeV)^2; also see reference 8.
[b]See reference 13.
[c]See reference 14.
[d]Upper limit (column 6)/[η(549 or 958)$\to$all modes]; see reference 9 for all other branching fractions.
[e]Number of events above background.
[f]The number of events expected is given for internal conversion or C-nonconserving, $T=0$, $\pi^+\pi^-$ decay each separately. Note that the two events observed are consistent with being due to $\rho\gamma$ internal conversion.
[g]The denominator is the branching fraction for $\eta(958)\to\eta_N+\pi^++\pi^-$ (see reference 9), and the 0.01 represents C-invariance violation in strong interactions. These upper limits have been discussed previously (see reference 3).

Table II. Asymmetries.

Mode	Events	$\frac{N_+-N_-}{N_++N_-}$[a]	Possible magnitude
$\eta(549)\to3\pi$	$0.8\times(89\ \eta_C)$	...[b]	≤0.05[c]
$\eta(958)\to\eta+\pi^++\pi^-$	$172\ \eta_N+\pi^++\pi^-$	-0.04 ± 0.08	$\ll0.01$[d]
	$89\ \eta_C+\pi^++\pi^-$	...[b]	
$\eta(958)\to\pi^++\pi^-+\gamma$	152 (all)	$+0.07\pm0.08$[e]	
	86 (near ρ)[f]	$+0.05\pm0.11$[e]	<0.10[g]

[a]$N_\pm$ is the number with $\cos\theta_{\pm\gamma}>0$; the error is $(N_++N_-)^{-1/2}$ for small asymmetry.
[b]Not attempted because of ambiguity in identification of the $\eta\to3\pi$ triplet among the five pions $(2\pi^++\pi^0+2\pi^-)$.
[c]See reference 4.
[d]Strong decay.
[e]See Reference 16.
[f]Subsample with $0.4<M^2(\pi^+\pi^-)<0.7$ (BeV)^2.
[g]See reference 17.

the C-noninvariant coupling does not violate isospin conservation.[18] It is hoped that the data given in this Letter will be of use in limiting the range of possible theoretical speculations regarding C-invariance violation.

We wish to acknowledge the support and cooperation of the many members of the Alvarez group and the Bevatron staff. We especially thank Professor Luis W. Alvarez for his support and encouragement, and for his hospitality to one of us (G.R.K.). We acknowledge with thanks helpful discussions with Professor E. C. Fowler, Professor S. L. Glashow, Professor T. D. Lee, Professor A. Pais, and Professor W. J. Willis.

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[6]A negative result on the decay $\eta(549\text{ MeV}) \rightarrow \pi^0 + e^+ + e^-$ has been reported by L. R. Price and F. S. Crawford, Jr., Phys. Rev. Letters 15, 123 (1965).

[7]T. D. Lee, Phys. Rev. 139, B1415 (1965); M. Nauenberg, "The $\eta \rightarrow \pi^+ + \pi^0 + \pi^-$ Decay with C-Violation" (to be published); J. Prentki and M. Veltman, Phys. Letters 17, 77 (1965).

[8]We denote the η at 549 MeV and the $\eta 2\pi$ resonance at 958 MeV as $\eta(549)$ and $\eta(958)$, respectively, because both appear to be $TJ^{PG} = 00^{-+}$ mesons [see G. R. Kalbfleisch, O. I. Dahl, and A. Rittenberg, Phys. Rev. Letters 13, 349a (1964); G. R. Kalbfleisch et al., Phys. Rev. Letters 12, 527 (1964); M. Goldberg et al., Phys. Rev. Letters 12, 546 (1964); M. Goldberg et al., Phys. Rev. Letters 13, 249 (1964); P. M. Dauber et al., Phys. Rev. Letters 13, 449 (1964)]. Also, we denote the decays $\eta(549) \rightarrow \pi^+ + \pi^0 + \pi^-$ and $\pi^+ + \pi^- + \gamma$ as η_C, and $\eta(549) \rightarrow$ all neutrals as η_N. We use $[\eta(549) \rightarrow \pi^+ + \pi^- + \gamma]/\eta_C \approx 0.2$, $[\eta(549) \rightarrow \pi^+ + \pi^0 + \pi^-]/\eta_C \approx 0.8$, and $\eta_C/[\eta(549) \rightarrow \text{all modes}] \approx 0.3$. [See A. H. Rosenfeld et al., Rev. Mod. Phys. 36, 977 (1964).]

[9]Kalbfleisch, Dahl, and Rittenberg, see reference 8.

[10]In addition, approximately 500 V-plus-0-, -2-, and -4-pronged events plus a Dalitz pair were measured as V-plus-2-, -4-, and -6-pronged events, respectively, and processed similarly. If a Dalitz pair had been noted in the original scanning, the event had been recorded as though the Dalitz pair were absent, and then a "flag" had been set to indicate it. The C-nonconserving decay modes involving an $e^{\pm}$ pair would not give "Dalitz-like" pairs in general; as expected, none of these events yielded any candidates.

[11]Those events that fit best as $\Lambda\eta_N e^+e$, $\Lambda\pi^0e^+e^-$, or $\Lambda e^+e^-\gamma$ were all examined on the scanning table for interactions, delta rays, and bremsstrahlung on the charged tracks in order to find any definite electron candidates. None were found.

[12]The 3 $\eta(549) \rightarrow \pi^0 + e^+ + e^-$ candidates are events fitting best as η_C but fitting $\pi^0e^+e^-$ with a probability greater than 0.1 of the η_C fit. The $(0 \pm 1)/0.33$ $\eta(958) \rightarrow \pi^0 + e^+ + e^-$ candidates are those in which either of the electrons had a momentum less than 200 MeV/c in the laboratory. The number 0.33 is the estimated fraction of such decays from a "fake" calculation (using the $\pi^0e^+e^-$ matrix element given in reference 4). We thank Professor W. J. Willis for the use of his program. The $\eta(958) \rightarrow \rho^0 + \pi^0$ candidates may be incorrectly identified $\rho^0\gamma$ events; also, the $\eta(958) \rightarrow \omega^0 + \pi^0$ candidates may be (C-conserving) $\omega^0\gamma$ or $\eta_C\pi^0\pi^0$ events, since these three hypotheses are experimentally indistinguishable.

[13]The numbers of events expected are based on a possible maximal violation of C invariance in electromagnetism. The C-nonconserving decay modes proceed with order α^2 and can be compared with other α^2 decay rates [$\eta(549 \text{ or } 958) \rightarrow 2\gamma$, for example]. The $\eta(549) \rightarrow 2\gamma$ rate is known to be approximately the same as η_C (see reference 8). The $\eta(958) \rightarrow 2\gamma$ mode has not yet been observed but is expected to be about 0.1 of the $\rho\gamma$ mode, or about 0.02 of the total rate. See L. M. Brown and H. Faier, Phys. Rev. Letters 13, 73 (1964); S. K. Kundu and D. C. Peaslee, Nuovo Cimento 36, 277 (1965); and R. H. Dalitz and D. G. Sutherland, "X^0-η Mixing and Some Radiative Meson-Decay Processes" (to be published). The decay $\eta(549) \rightarrow \pi^0 + e^+ + e^-$ is suppressed by SU(3) + CPT invariance [see N. Cabbibo, Phys. Rev. Letters 14, 965 (1965), theorem 9]. The decay $\eta(958) \rightarrow \pi^0 + e^+ + e^-$ is not suppressed by SU(3). Thus $\eta(549) \rightarrow \pi^0 + e^+ + e^-$ can proceed via mixing from the $\eta(958)$ at 0.01 of the total rate (see reference 4), as well as by a comparable amount due to SU(3)-breaking interactions. The $\eta(958) \rightarrow \pi^0 + e^+ + e^-$ proceeds unsuppressed at about the 2γ rate (see references 3 and 4) plus some contribution from SU(3)-breaking interactions introduced by mixing from $\eta(549)$. The $\eta(958) \rightarrow \eta(549) + e^+ + e^-$ is suppressed by phase space (references 3 and 4). The $(\pi^+\pi^-)_{T=0}e^+e^-$ modes are, apart from any SU(3) suppressions, at a rate about that of internal conversion, which is of order $\alpha(\pi^+\pi^-\gamma$ rate). We note that all C-nonconserving modes (of order α^2) can proceed at order α^4 without C-nonconservation.

[14]The previously reported result of 0 ± 1 $\eta(549) \rightarrow \pi^0 + e^+ + e^-$ candidates with an upper limit of 4 (see reference 6) is also less than the expectation of $0.03 \times [219$ $\eta(549) \rightarrow \pi^+ + \pi^0 + \pi^-] \simeq 7$ events.

[15]The asymmetry can also be described by an asymmetry parameter α. The decay of a $TJ^{PG} = 00^{-+}$ particle into $\pi^+\pi^-\gamma$ gives an intensity distribution,

$$I = N^* \sin^2\theta(1 + \alpha\cos\theta + \beta\cos^2\theta),$$

for p-wave, C-conserving and d-wave, C-nonconserving amplitudes (see reference 4). The N^*, α, and β contain the momentum dependencies, including any resonent Breit-Wigner terms. The asymmetry parameter α is obtained from the moments of $\cos^n\theta$,

$$\alpha = 8\langle\cos\theta\rangle/(3 - 7\langle\cos^2\theta\rangle).$$

All 152 events give $\alpha = 0.55 \pm 0.42$, and the 86 events near the ρ give $\alpha = 0.04 \pm 0.24$.

[16]The value of 0.10 for the $\pi^+\pi^-\gamma$ asymmetry parameter can be obtained for a p- to d-wave amplitude ratio equal to one at the peak of the ρ resonance. Since the ρ amplitude dominates $\eta(958) \rightarrow \pi^+ + \pi^- + \gamma$, a considerably smaller d-wave amplitude might be expected.

[17]An example is the A parity of J. B. Bronzan and F. E. Low, Phys. Rev. Letters 12, 522 (1964). The decay $\pi^0e^+e^-$ can proceed through the internal emission and absorption of a virtual photon, so that $\pi^0e^+e^-$ has $A = -1$. Kundu and Peaslee (reference 14) believe that the $\eta(958)$ has $A = +1$, so that $\eta(958) \rightarrow \pi^0 + e^+ + e^-$ and that part of $\eta(549) \rightarrow \pi^0 + e^+ + e^-$ arising from the singlet-octet mixing would be suppressed. The $\eta(549) \rightarrow \pi^0 + e^+ + e^-$ [and $\eta(958)$ from the "mixing"] can still

have a component arising from SU(3)-invariance violating interactions.

[18]The possibility that the C-nonconserving interactions conserve isospin has been considered by Prentki and Veltman (reference 5), and by T. D. Lee, "Classification of All C-Noninvariant Electromagnetic Interactions and the Possible Existence of a Charged, but $C=1$, Particle" (to be published).

POLARIZATION IN $\pi^- + p$ ELASTIC SCATTERING AT 2.08 GeV/c†

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As part of a program to study the high energy pion-nucleon interaction, we have measured the differential cross section (DCS) and polarization (P) in $\pi^- + p$ elastic scattering at an incident pion-laboratory momentum of 2.08 GeV/c. This momentum is particularly interesting as it is near the center of a 2-mb peak observed in the $\pi^- p$ total cross section measured as a function of energy.[1,2] This peak could correspond to a resonance in the isospin-$\frac{1}{2}$ system with a mass of 2190 MeV/c^2.[2,3] In addition, measurements by Damouth, Jones, and Perl of the DCS at 2.01 GeV/c exhibit, as well as the forward diffraction peak, considerable scattering at larger angles, including a prominent peak at $\cos\theta_\pi(\text{c.m.}) = 0.2$ or $-t = 1.2$ $(\text{GeV}/c)^2$, where t is the square of the four-momentum transfer.[4] These authors proposed that this second maximum is related to the peak in the total cross section at 2.08 GeV/c.

Other ideas have been put forward to explain the scattering at larger angles—for instance, the presence of a strongly interacting nucleon core,[5] or the formation of a compound nucleon which decays in a statistical way to many channels, including the elastic channel.[5,6] The second maximum has been interpreted by Simmons[7] as a second diffraction peak resulting from a most elementary optical model which considers only uniform absorption. Perl and Corey[8] obtained a much better fit to the data of reference 4, again using a purely absorptive model, but allowing the absorption to vary with the angular momentum l. Even this fit does not reproduce the details of the angular distribution. This indicates that a purely absorptive model is not sufficient. It is not at all certain that the second maximum is related to the peak observed in the $\pi^- p$ total cross section, since similar (although not so prominent) second maxima are observed in $\pi^+ p$ and $K^- p$ scattering.[4,9]

It has been pointed out that all these discussions have completely neglected spin effects,[10] and in fact our polarization measurements show that the usual assumption of a single scalar amplitude to describe elastic scattering in this energy region is not valid.

The experiment was carried out at the Argonne zero gradient synchrotron with a polarized proton target. Negative pions produced at zero deg from a 10-cm-long Cu target were directed to the apparatus shown in Fig. 1 by a standard beam transport system. At the polarized target the pion intensity was typically 1 to 2 $\times 10^5$ pions per pulse over an area 1.6 cm vertically $\times$ 2.5 cm horizontally and with $\Delta p/p = \pm 1.7\%$. Electrons were electronically removed by a gas Čerenkov counter,[11] and the beam was monitored and defined by the counters 1, 2, and $\bar{3}$.

The polarized target is similar to others already described[12,13] and uses rectangular crystals of $(0.99\text{ La} + 0.01\text{ Nd})_2\text{Mg}_3(\text{NO}_3)_{12} \cdot 24\text{ H}_2\text{O}$ stacked to give a scatterer 1.9 cm vertically $\times$ 2.9 cm horizontally $\times$ 3.8 cm long. The crystals are at the center of a magnetic field of 18.67 kG.

Figure 1 also shows schematically the arrangement of counters and electronic logic for the detection of elastic scattering from the free protons of the target crystals. Scatterings in the vertical plane were measured with an acceptance in azimuthal angle of about ±10 deg.