intercomparison of photoproduction amplitudes using various assumptions about quarks by L. S. Kisslinger and H. Feshbach, Ann. Phys. (New York) 66, 651 (1971).

[11] This cancelation is demonstrated experimentally by the lack of bumps in the 0° and 180° differential cross sections. This becomes an input to the quark models and is used to evaluate the radial–wave-function parametrization with respect to the quark magnetic moments. However, some recent data by T. Fujii, H. Okuno, S. Orito, H. Sasaki, T. Nozaki, F. Takasaki, T. Takikawa, K. Amako, I. Endo, K. Yoshida, M. Higuchi, M. Sato, and Y. Sumi, Phys. Rev. Lett. 26, 1672 (1971), shows a small "bump" in π^+ photoproduction at 180°.

[12] See the Argand diagrams in A. Rittenberg *et al.* (Particle Data Group) Rev. Mod. Phys. 43, S1 (1971).

Search for $\bar{\nu}_e + e^-$ Scattering*

Henry S. Gurr, Frederick Reines, and Henry W. Sobel
Department of Physics, University of California at Irvine, Irvine, California 92664

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An improved cross-section upper limit of 1.9 times that of $V-A$ theory is determined for the reaction $\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^-$. The target, a 7.84-kg plastic scintillator, was enclosed by a composite 330-kg NaI and 2200-liter liquid anticoincidence detector, and was operated in a fission $\bar{\nu}_e$ flux of 2.2×10^{13} cm^{-2} sec^{-1}. We note some constraints which this limit imposes on theoretical conjectures.

In this Letter we present the current status of our continuing search for the elastic scattering of electron antineutrinos $\bar{\nu}_e$ by electrons using a fission reactor as a $\bar{\nu}_e$ source.[1] As will be seen, we have substantially improved the previous elastic scattering cross-section upper limit (<4 times that of $V-A$ theory), enabling us to place more restrictions on the interactions which are permitted. The equipment is much the same as that reported earlier except for some additions designed to reduce backgrounds. The results also reflect an increase in total run time from the 15 days on which the first report was based, to 147 days, live time. In brief, the detector consisted of a 7.84-kg segmented plastic scintillator target block entirely surrounded by a 330-kg NaI anticoincidence detector[1] which was in turn enclosed by a 2200-liter liquid anticoincidence detector. The elastic scattering mode accepted only events occurring in the plastic, in anticoincidence with these outer detectors. The system was operated concurrently in the mode designed to detect inverse β decay, $\bar{\nu}_e + p \rightarrow n + e^+$, in the plastic target, so as to study the background from this reaction as well as to determine the fission $\bar{\nu}_e$ spectrum. Changes made in the detector included the addition of 2.5 cm of Pb around the NaI scintillator (for a total of 6.3 cm) to provide further shielding against reactor γ rays. A cadmium sheet immediately external to the Pb reduced the γ background arising from neutron capture. Further shielding against reactor neutrons and γ's was provided by the addition of water tanks where practicable. The result of these measures was to reduce the reactor-associated rate as measured by the NaI detector from $R = 1.3 \pm 0.4$ counts/min in the 4.1–10.3-MeV region to levels consistent with statistical fluctuation in the rate of radioactivity, i.e., $R \leq 0.15$ counts/min. Cosmic-ray–associated backgrounds were reduced by the addition of a large rectangular liquid anticoincidence detector (2.59 m × 1.43 m × 0.28 m) above the cylindrical liquid anticoincidence detector. Measurements of events associated with muons, such as those due to neutrons and those produced by muon capture which lead in turn to decays of B^{12} (end point, 13.4 MeV), suggested the incorporation of electronic vetoes which were effective in a large fraction of these cases.

The rapidly falling spectrum characteristic of the background makes it essential to maintain a continuous check of the system gain. Such a check is provided by the β decay (3.2-MeV end point) of Bi^{214} contaminant. The procedure used was to measure the rate of Bi^{214} decay as identified by a delayed daughter α particle (7.7 MeV), $\tau_{1/2} = 164$ μsec. The energy associated with a preselected Bi^{214} rate was taken as the reference value and all runs were normalized to it. The absolute energy scale was set to within ± 2% by means of a Tl^{206} γ source (2.62 MeV). Both sources were viewed by the entire plastic in anticoincidence with the surrounding NaI. The mean correction to the overall gain of the system as measured by the B^{214} was within ± 2%. Figure 1 shows these calibration spectra.

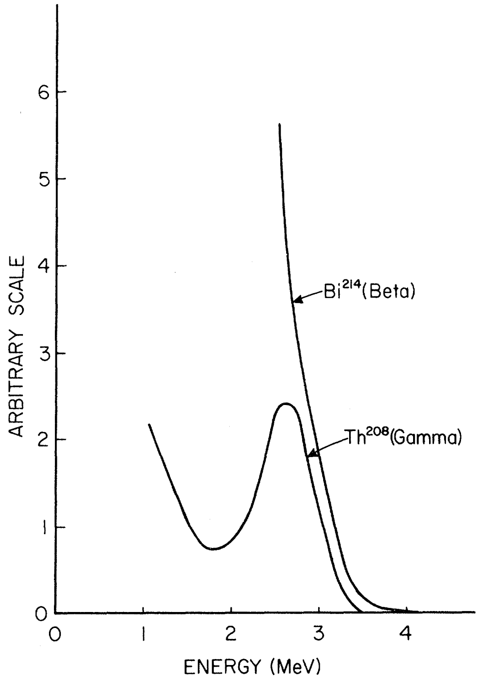

FIG. 1. Calibration spectra.

Table I shows the observed plastic-detector events in the elastic scattering mode in the energy range 3.0–5 MeV for the reactor "on" (95 days) and "off" (52 days). We selected only events which occurred in a single plastic element and thereby reduced background, arising principally from γ rays, to $\frac{1}{3}$ the total rate. The rates with reactor on, R_{on}, and reactor off, R_{off}, and run times have been corrected for dead time (~22%). Also shown in Table I are $R_{\text{on}} - R_{\text{off}} = \Delta_{\text{expt}} \pm \delta$, where δ is the statistical uncertainty, and Δ_{V-A} the rate predicted by the $V-A$ theory.[2,3] The $V-A$ predictions take into account the increase in rate due to detector energy resolution (12% half-width at half-maximum), and a decrease in rate (~40% due to electrons escaping a single plastic element). Also included in the predicted rate is a statement of errors based on the uncertainties in the fission $\bar{\nu}_e$ spectrum and in the β-decay coupling constants.[4] More explicitly, the calculation of Δ_{V-A} involves the following:

$$\Delta_{V-A} = N_e \eta \int_{E_{\text{min}}}^{5\,\text{MeV}} S(E)\, dE;$$

$S(E) = \int f(E')\sigma(EE')\,dE'$ is the $V-A$-theory elastic scattering recoil spectrum for fission neutrinos[4]; $\sigma(E,E')$ is the $V-A$ elastic scattering cross section[2]; $N_e = 2.52 \times 20^{27}$ electrons, the number of electrons in our plastic target; $\eta = 0.65$, the detector efficiency correction for recoil electrons that escape a single detector element; $k = 1.098$, the correction for spectrum shift due to detector energy resolution; and $f(E')$ is the differential spectrum of fission antieutrinos.

The Reactor-associated backgrounds are as follows:

(*a*) $\bar{\nu}_e + p \to n + e^+$.—Inverse β decay produces in our detector a recoil positron which will masquerade as an elastic scattering event if we fail to detect *both* of the accompanying positron annihilation γ's *and* the delayed neutron-capture γ's. Fortunately, we can estimate this source of background by measurements of the annihilation γ detection efficiency for positrons in the plastic detector and the neutron detection efficiency for neutrons from inverse β decays in the plastic detector.

If we denote the probability of observing a single annihilation γ as η_γ, and the probability of seeing at least one of the neutron-capture γ's as η_n, then the probability of an inverse β-decay event masquerading as an elastic scattering event is given by $P = (1-\eta_n)(1-\eta_\gamma)^2$. From observation of positron annihilation in our detector, for those events exhibiting neutron capture, we conclude that $\eta_\gamma = 0.85^{+0.02}_{-0.03}$. The neutron detection efficiency is estimated to be ~0.2 by comparing the rate of observed inverse β decays with the predicted rate. Hence $P \approx (1-0.2)(1-0.85)^2 = 0.018$. The number of $\bar{\nu}_e + p$ reactions per day in our plastic target capable of depositing between 3.6 and 5.0

TABLE I. Experimental results and theoretical predictions for plastic detector (7.84 kg).

E_{min} (MeV)	R_{on}	Rates (counts/day, $E_{\text{min}} \leq E \leq 5$ MeV) R_{off}	$\Delta_{\text{expt}} \pm \delta$	Δ_{V-A}	Ratios $\Delta_{V-A}/R_{\text{off}}$	δ/Δ_{V-A}
3.0	6.43 ± 0.26	6.49 ± 0.35	−0.06 ± 0.44	0.40 ± 0.03	0.06	1.10
3.2	3.28 ± 0.18	3.49 ± 0.35	−0.21 ± 0.31	0.29 ± 0.02	0.08	1.06
3.4	1.82 ± 0.18	1.81 ± 0.18	0.01 ± 0.22	0.21 ± 0.02	0.13	1.05
3.6	1.05 ± 0.11	0.90 ± 0.13	0.15 ± 0.17	0.16 ± 0.01	0.18	1.06
3.8	0.68 ± 0.08	0.54 ± 0.10	0.14 ± 0.13	0.12 ± 0.01	0.22	1.25

MeV in a single plastic element is calculated to be 6.2/day. This calculation took into account the fraction of single-element events which we measured with our detector and allowed for the 1-MeV annihilation energy which added to the positron recoil energy in these cases. The number mistaken as elastic scattering is approximately $(0.018)(6.2/\text{day}) = 0.11/\text{day}$.

(*b*) *Neutrons.*—It can be imagined that neutrons produce background events by direct recoil from protons in the plastic. However, this process is discriminated against by the poor scintillation efficiency of the plastic for recoil protons in the relevant energy range. (It is ~0.5 times that for electrons at ~6 MeV.) Neutrons of the requisite energy, >6 MeV, cannot arise from natural photo processes.

A test of maximum possible neutron-associated background was made using a Pu-Be source. It produced a count rate in the NaI detector of 92.9/min (4–10 MeV) and a single-element rate of 0.002/min in the plastic detector (3.6–5.0 MeV). The reactor-associated background in the NaI was measured to be $\lesssim 0.15/\text{min}$. Assuming the neutron spectrum from the reactor to be as energetic as that associated with the source *and* further assuming that all the annulus up-down difference is due to neutrons, we find that the maximum reactor-associated background in the plastic arising from neutrons is

$$(0.15/92.9)(0.002/\text{min})(1440\ \text{min/day}) = 0.005/\text{day}\ (3.6\text{–}5.0\ \text{MeV}).$$

(*c*) *Gammas.*—Although reactor-associated γ's probably arise in large measure from neutron capture, we make a separate limit for completeness. Deductions as to the maximum background contribution from these γ's can be made by comparing reactor-associated rates in the NaI anticoincidence detector before the addition of 6.3 cm of Pb outside the NaI (12/min) and scaling the pre-Pb plastic rate (6/day):

$$(0.15/12)(6/\text{day}) = 0.075/\text{day}.$$

Since $\frac{1}{3}$ of these will be single-element events, we obtain a maximum background due to reactor-associated γ's of 0.025/day (3.6–5.0 MeV).

The sum of the above reactor-associated backgrounds (~0.14/day) is approximately the same as our observed reactor on-off difference (for $E_{\text{min}} = 3.6$ MeV), and the data suffer from a large statistical uncertainty. We chose the results for $E_{\text{min}} = 3.6$ MeV as a compromise between minimizing $\delta/\Delta_{V\text{-}A}$ and maximizing $\Delta_{V\text{-}A}/R_{\text{off}}$. Based on the data in Table I, we find a 1-standard-deviation upper limit on this elastic scattering signal of $0.15 + 0.17 - 0.14 = 0.2/\text{day}$. This corresponds to an elastic scattering cross-section limit $\sigma_{\text{expt}} < 6 \times 10^{-47}\ \text{cm}^2$ per fission $\bar{\nu}_e$ for production of recoil electrons in the energy range 3.6–5.0 MeV.

It is apparent from Table I that we are searching for a small elastic-scattering signal superimposed on a very rapidly falling background. Thus, gain shifts which may be $\leq 1\%$ could produce count-rate shifts $\leq 0.1/\text{day}$. Hence, in the interest of a conservative upper limit, we arrive at the result, relative to the $V - A$ prediction, in this energy range

$$\sigma_{\text{expt}}/\sigma_{V\text{-}A} < (0.2 + 0.1)/0.16 < 1.9.$$

Figure 2 indicates the limits which these data place on various theoretical possibilities.[5,6]

Consideration of the data in Table I indicates that the system used in these measurements was seriously limited by the small target mass and a high background which placed a premium on instrumental stability. An estimate shows that the primary source of background was from unlabeled Bi^{214} decay. Accordingly, we have rebuilt the detector, doubling the size of the plastic target and thinning the aluminized Mylar optical dividers to $5.3 \times 10^{-4}\ \text{g/cm}^2$ in order to make visible the otherwise absorbed α particle which follows the Bi^{214} decay. In addition, we have lowered the unlabeled inverse β background by removing the MgO packing material, which separated the NaI and plastic scintillators. Preliminary runs with the modified system indicate a marked reduction in the background from unlabeled B^{214}.

It is a pleasure to thank A. A. Hruschka for his

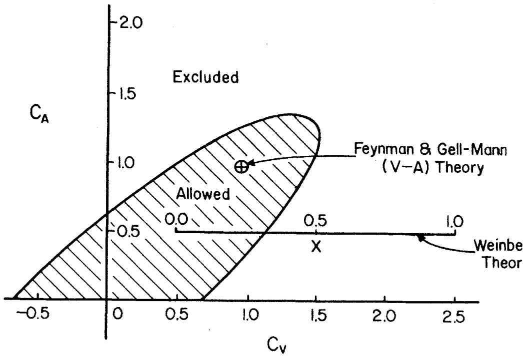

FIG. 2. Experimental limits for the vector, C_V, and axial-vector, C_A, coupling constants appropriate to the $\bar{\nu}_e + e^-$ elastic scattering process.

help in designing and installing the additional anticoincidence detector and the Pb-Cd and water shields. We gratefully acknowledge continued hospitality of the E. I. Dupont de Nemours Company which operates the Savannah River Plant for the U. S. Atomic Energy Commission.

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[3] L. Heller, Los Alamos Scientific Laboratory Report No. 3013, 1964 (unpublished).

[4] F. T. Avignone, Phys. Rev. D 2, 2609 (1970).

[5] For a discussion of limits placed by earlier results see H. H. Chen, Phys. Rev. Lett. 25, 768 (1970); H. H. Chen and B. W. Lee, Phys. Rev. D (to be published).

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Direct Emission in $K^\pm \to \pi^\pm\pi^0\gamma$

Saul Barshay and Jens Hvegholm
The Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark

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We present the results of a calculation of a part of the direct-emission amplitude in $K^\pm \to \pi^\pm\pi^0\gamma$ for which an unambiguous, finite, gauge-invariant expression is obtainable in terms of known parameters. The amplitude produces a small distortion of the Dalitz plot through its destructive interference with the bremsstrahlung amplitude.

Currently, there are two independent experimental studies[1,2] of the decays $K^\pm \to \pi^\pm\pi^0\gamma$ in the course of being analyzed. The information to be derived from these experiments concerns (1) the possible existence and nature of a direct emission amplitude, and (2) if the latter does exist, the possibility of a CP-invariance-violating asymmetry between the $K^\pm$ decay distributions.[3,4,5] On the theoretical side, estimates of various possible contributions to the direct-emission amplitude are necessarily very model dependent. However, there is one (small) piece of this amplitude for which an unambiguous, finite, gauge-invariant expression is obtainable in terms of known parameters. This amplitude is in the nature of a rescattering correction to the usual bremsstrahlung amplitude and corresponds to the matrix element from the sum of Feynman diagrams in Figs. 1 and 2. The matrix elements from Fig. 2 do not vanish because the ρ is virtual, and are necessary for the gauge invariance. The effective interaction Hamiltonian density for the calculation is

$$\begin{aligned}H=\Big\{&-ie[\pi^-(\partial_\mu\pi^+)-(\partial_\mu\pi^-)\pi^+]A_\mu-ie[K^-(\partial_\mu K^+)-(\partial_\mu K^-)K^+]A_\mu+ie[\rho_\nu^-(\partial_\mu\rho_\nu^+)-(\partial_\mu\rho_\nu^-)\rho_\nu^+]A_\mu\\&+ie[(\partial_\nu\rho_\mu^-)\rho_\nu^+-\rho_\nu^-(\partial_\nu\rho_\mu^+)]A_\mu+ig[\pi^0(\partial_\mu\pi^+)-(\partial_\mu\pi^0)\pi^+]\rho_\mu^-+ge\pi^0\pi^+\rho_\mu^-A_\mu+GK^-\pi^+\pi^0\Big\}+\text{H.c.}\qquad(1)\end{aligned}$$

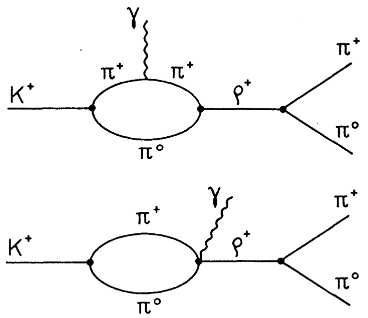

FIG. 1. Feynman graphs leading to a finite effective direct-emission amplitude.

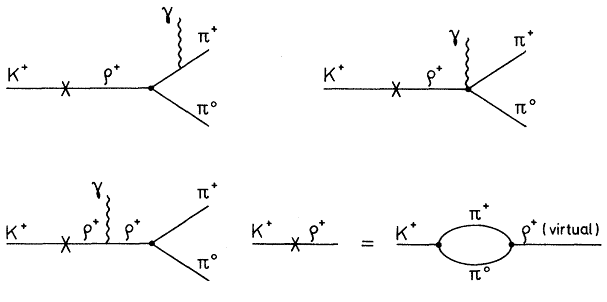

FIG. 2. Additional Feynman graphs leading to the finite, gauge-invariant direct-emission amplitude in Eq. (2).