with $\vec{p}_1$, $\vec{p}_2$, and $\vec{p}_4$ equal, respectively, to the three-momentum of the initial proton, the outgoing π^-, and the outgoing neutron.

Figure 2(c) shows the $\cos\theta_{\pi^- p}$ distribution for events in the ρ-mass region 650-850 MeV, while Figs. 2(b) and 2(d) show the $\cos\theta_{\pi^- p}$ distribution for mass regions below and above the ρ. A small $\sin^2\theta_{\pi^- p}$ effect is seen for the ρ region, while the distributions averaged for masses above and below the ρ are approximately isotropic. The Treiman-Yang angular distributions for the same mass regions are shown in Figs. 2(e)-2(g). The Treiman-Yang angular distribution for the ρ region is very anisotropic and peaked toward 0°. For the regions above and below ρ, the Treiman-Yang distributions are approximately isotropic, becoming slightly anisotropic when the $\Delta^-(1236)$ events are removed (shaded area of graph).

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UPPER LIMIT FOR ELASTIC SCATTERING OF ELECTRON ANTINEUTRINOS BY ELECTRONS*

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A conservative upper limit of 4 times the prediction of $V-A$ theory has been determined for the process $\bar{\nu}_e + e^- \to \bar{\nu}_e + e^-$. The target detector used in a fission $\bar{\nu}_e$ flux of 2.8×10^{13} cm^{-2} sec^{-1} was a 7.84-kg plastic scintillator arrangement enclosed by 330 kg of NaI and a 2200-liter liquid detector, the latter two operated in anticoincidence with the plastic.

Experimental information regarding the antineutrino-electron scattering process $\bar{\nu}_e + e^- \to \bar{\nu}_e + e^-$ is of great interest to weak-interaction physics because it is a collision between two elementary particles which do not possess the strong interaction. Furthermore, the particles involved are in some sense nature's simplest, since they are stable end products of the weak interaction. The purpose of the present communication is to report recent progress in a program to test the predictions of the $V-A$ theory in this so far experimentally unchecked case.[2] The $\bar{\nu}_e$ source is one of the large fission reactors at the Savannah River Plant.

The experimental design is dictated by the requirement to discriminate against all reactions but the one of interest in the face of the fact that the expected cross section—assuming the theory of Feynman and Gell-Mann[3]—is so small and the resultant reaction seemingly nondescript. It early became clear that an overwhelming source of background promised to be due to gamma rays

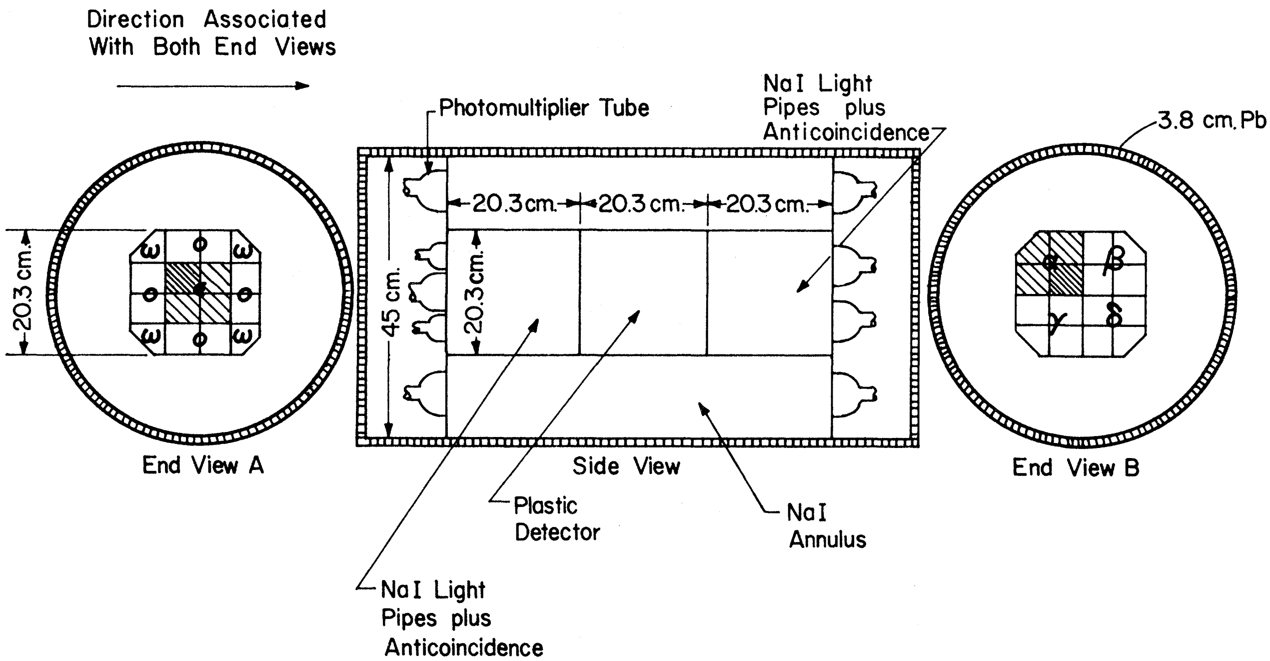

FIG. 1. Schematic of composite NaI, plastic scintillation detector. The inner plastic detector consisting of 16 plastic scintillating bars, each wrapped in aluminized Mylar, is viewed by photomultiplier tubes through NaI light pipes. The arrangement enables specification of the plastic bars in which the event took place. One end of the plastic bars is viewed by four NaI pipes labeled α, β, γ, and δ as shown in the figure labeled end view B, and the other end marked A is viewed in groups of four labeled ϵ, θ, Φ, and ω. An ϵ,α coincidence is shown in the figure. Pulse shape difference is used to discriminate pulses in the plastic and the NaI light pipes. The NaI annulus completes the 4π anticoincidence shield.

and this gave rise to the detector used.[4] The essential idea around which the detector is designed is that gamma rays will preferentially tend to Compton scatter rather than be absorbed in a low-Z medium.[5]

A spatial anticoincidence can be expected to discriminate in favor of the single electron pulse such as that expected from the elastic scattering process and against the sequence of gamma-ray scatterings produced in a low-Z medium. The detector, shown schematically in Fig. 1, incorporates a segmented core made up of 16 close-packed, optically isolated scintillating plastic bars totaling 7.84 kg. These bars are viewed through NaI scintillators and are surrounded by a NaI annulus operated in anticoincidence. The result is a plastic detector entirely surrounded by at least 10.7 cm of NaI. Advantage is taken of the widely different pulse shapes from the plastic and NaI scintillators and the address of the event to determine whether the scintillation was produced in the plastic or NaI light pipes. The entire system was immersed in a large liquid detector[6] which served as a further neutron, gamma ray, and cosmic-ray anticoincidence shield. The system was almost completely encased in water tanks inside a lead shield 20-cm thick.

Signals from the various photomultiplier tubes were routed as shown in Fig. 2. Fan-out circuits divided the signal sending one set to the oscilloscope display and the other to a trigger logic which selected combinations of interest. The trigger constraints imposed required a fast plastic pulse[7] (~20 nsec) seen in coincidence by the photomultiplier tubes which viewed both sides of the plastic, and in anticoincidence with pulses in the NaI annulus detector. The runs here reported were made with the plastic thresholds set at 2 MeV and the NaI anticoincidence level set at ~40 keV. Further selection of the pulses was made by reading the oscilloscope record. Inspection of the scope trace gives the plastic bar in which the event occurred and the energy of the event and reveals the presence or absence of a liquid and annulus anticoincidence pulse. In addition, such inspection allowed rejection of triggers due to events which occurred partially in the NaI light pipes and in the plastic. The system was calibrated and checked for stable oper-

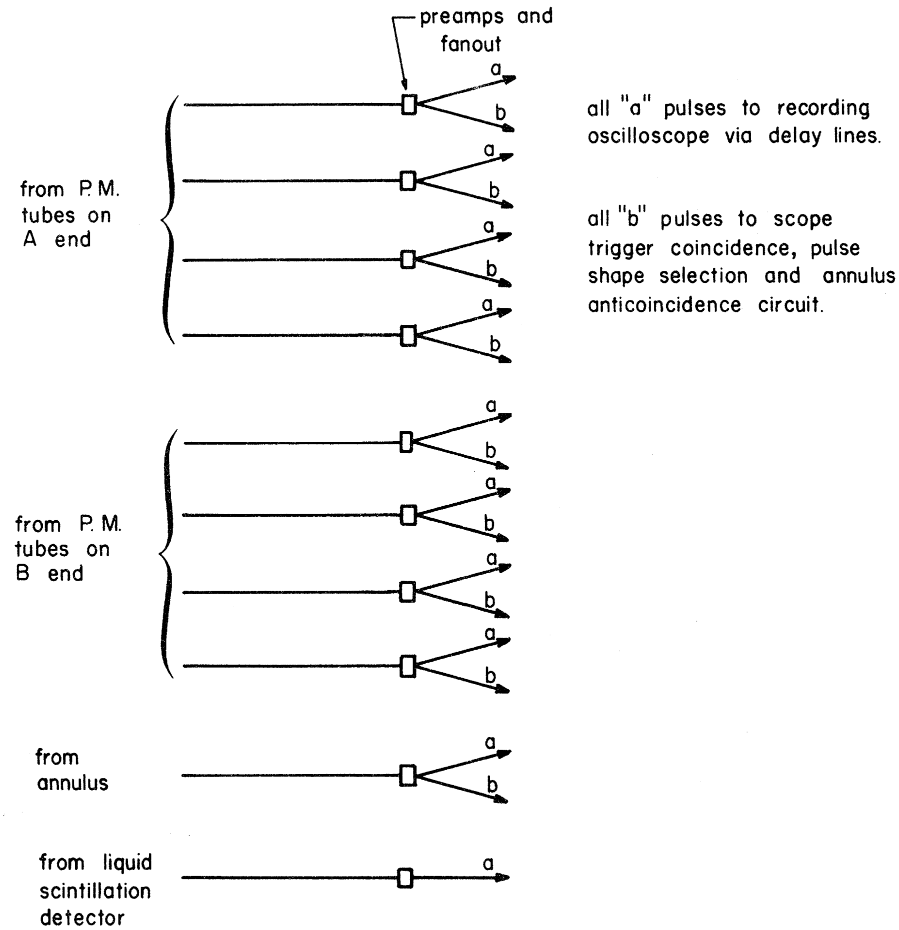

FIG. 2. Logical schematic of electronics.

ation by means of gamma rays from Co^{60} (1.17, 1.33 MeV) and Tl^{208} (2.62 MeV) sources. A continuous internal calibration was unwittingly provided by a contaminant of the plastic detector, i.e., Bi^{214}, a daughter of the ubiquitous Ra family. The Bi^{214} was recognized by the pair of pulses it produced when it and its daughter Po^{214} decayed:

$$Bi^{214} \to Po^{214} + e^- + \bar{\nu}_e \quad \text{(end point 3.2 MeV)}$$
$$\quad\quad \llcorner\!\!\to Pb^{210} + \alpha \quad \text{(7.7 MeV)}.$$

The electron background from the Bi^{214} made it necessary to restrict our search for electrons with energies >3.6 MeV. K^{40} (1.46 MeV) was also a useful internal contaminant. Details of the detector and circuitry will be published elsewhere.

A sequence of runs was made in which we observed the plastic rate unaccompanied by NaI or liquid scintillator pulses with the reactor on and off. Also measured was the NaI annulus rate in anticoincidence with the liquid scintillator. The following table summarizes the relevant data:

Reactor	Annulus rate 4.1-10.3 MeV (min^{-1})	Plastic rate 3.8-5 MeV (day^{-1})
On	18.6 ± 0.3	1.25 ± 0.44
Off	17.3 ± 0.2	1.17 ± 0.30

The energy ranges were chosen to optimize the ratio of expected signal to background. The listed errors are statistical in origin. The annulus rate associated with the reactor, $1.3 \pm 0.4\ min^{-1}$, indicates the gamma-ray background against which the plastic detector NaI combination discriminates.

The reactor-associated plastic rate Δ is seen from the table to be $\Delta = (0.08 \pm 0.53)$/day. This result indicates that an upper limit of 0.6/day can be cited for the reactor-associated signal with a confidence level of 84%.

Several sources can be expected to contribute to this signal. The reactor-associated rate prior to the addition of the 3.8-cm internal Pb shield was measured to be (5.3 ± 1.7)/day. Since the gamma-ray attenuation of the Pb is ~10, we estimate a residual gamma rate of ~0.5/day. In addition, we expect a reactor-associated rate due to inverse beta decay ($\bar{\nu}_e + p \rightarrow n + e^+$) in the plastic and the surrounding liquid. However, in view of the large uncertainty in the value of Δ, we make no attempt to assess the contribution due to inverse beta decay nor do we subtract the estimated residual effect of gamma rays. The upper limit on the cross section for the production of recoil electrons in the range $3.8 < E < 5$ MeV is arrived at in this way:

$$\sigma_e < R/(n_e f \eta),$$

where $R = 0.6$/day, upper limit on $\bar{\nu}_e + e^-$ signal; $n_e = 2.52 \times 10^{27}$, number of electrons in plastic target; $f = 2.4 \times 10^{18}$, $\bar{\nu}_e$ flux ($\mathrm{cm}^{-2} d^{-1}$); $\eta = 0.79$, correction for effect of detector energy resolution on the rapidly falling electron-recoil spectrum predicted by $V-A$ theory (+3 %) and for overall detector dead time (−23 %); and $\sigma_e < 1.3 \times 10^{-46}$ cm^2 per fission $\bar{\nu}_e$. The result may be compared with the cross section σ_{th} predicted by using the Feynman-Gell-Mann theory,[1,8]

$$\sigma_{\mathrm{th}} = (3.3 \pm 0.3) \times 10^{-47} \text{ cm}^2 \text{ per fission } \bar{\nu}_e$$

or

$$\sigma_e / \sigma_{\mathrm{th}} = g^2 / g_\beta^{\,2} < 4.$$

It therefore appears at this stage in the experiment that the results are not incompatible with the value of the cross section predicted by $V-A$ theory.

Although it is clear that longer runs will improve the quality of the data, it was felt that various changes in the equipment merited prior consideration. Changes now in process include an increase in the internal Pb shield thickness by 2.5 cm, more external shielding, and an enlarged cosmic-ray anticoincidence shield, which show promise of reducing all backgrounds, with the possible exception of $\bar{\nu}_e + p \rightarrow n + e^+$ in the plastic detector itself,[9] below the $V-A$ prediction for the elastic scattering process.

The development of the composite plastic-NaI detector was assisted primarily by A. A. Hruschka and F. Dix. H. Sobel, W. Kropp, M. Moe, and M. Crouch were most helpful during the course of the experiment, and J. Brooks assisted with various numerical calculations. E. Stewart of the Harshaw Chemical Company, which fabricated the detector, was most cooperative, and the hospitality of the E. I. DuPont de Nemours Company, which operates the Savannah River Plant for the U. S. Atomic Energy Commission, is noted with appreciation. The moral support of Professor John A. Wheeler is gratefully recorded.

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[4]Earlier in the course of this work, the reactor-associated signal ranged from one to three orders of magnitude above the limits we report in this paper. Subtleties associated with the earlier data led for a time to the incorrect conclusion that this signal was due to neutrinos. The addition of 3.8 cm of Pb internal to the liquid scintillator entirely enclosing the plastic NaI detector showed that the reactor-associated signal *prior* to the addition of the Pb was, in fact, almost completely attributable to gamma rays.

[5]For a description of the experimental approach see F. Reines, Ann. Rev. Nucl. Sci. 10, 1 (1960).

[6]For details of the liquid detector, see T. L. Jenkins, F. E. Kinard, and F. Reines, Phys. Rev. 185, 1599 (1969). This is the detector used to observe the reaction $\bar{\nu}_e + d \rightarrow n + n + e^+$, except that the central Mylar bag and aluminum septum were removed for the elastic scattering experiment.

[7]The Tl activated NaI pulses are characteristically

~ 250 nsec in duration.

[8]This cross section is based on the recent analysis by F. T. Avignone of all available data on the beta spectrum from fission. We are grateful to Dr. Avignone for communication of his results prior to publication. See also, F. T. Avignone, III, S. M. Blakenship, and C. W. Darden, III, Phys. Rev. 170, 931 (1968).

[9]The $\bar{\nu}_e + p$ reaction in the liquid anticoincidence detector can give a signal in the plastic by gammas from capture of the product neutron in the NaI which surrounds the plastic. An improved experiment now under way will effectively eliminate this source of background by adding a thin Cd sheet external to the 3.8-cm Pb shield which absorbs the neutron-capture gammas prior to their entry into the NaI and the plastic detector. Consideration of the signal from $\bar{\nu}_e + p$ in the plastic target itself gives hope of adequately discriminating against this source of background as well via the two 0.51-MeV annihilation gammas and the associated neutron.

HADRON-NUCLEUS TOTAL CROSS SECTIONS

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Total cross sections for collisions between high-energy hadrons and nuclei are calculated using both Woods-Saxon and Gaussian density distributions for the nuclei. Comparisons with measurements are made. Errors incurred by truncating multiple-scattering series are investigated.

Many analyses of high-energy hadron-nucleus collisions have been based upon a diffraction approximation due to Glauber.[1] This approximation is most accurate for small-angle collisions. Consequently it is not unreasonable to expect that high-energy hadron-nucleus total cross sections, which depend only upon the corresponding hadron-nucleus forward elastic scattering amplitudes, could be calculated quite reliably for a given nuclear model. Such calculations have been carried out for a simple model in which nuclei are described by Gaussian density distributions.[2-4] Such a model, although quite unrealistic, is extremely useful because it leads to an analytic expression for the total cross sections which exhibits qualitative features that are likely to reappear in more realistic calculations.

We have performed analyses of total cross sections with a model in which the nuclei have Gaussian density distributions and with a model in which the nuclei have Woods-Saxon shapes for their density distributions. The quantitative results obtained with these two models differ by as much as 15%. Although such differences may seem relatively small, they are significant since the measurements have uncertainties considerably smaller than 15%. Nevertheless the qualitative results are clearly not very sensitive to the nuclear model. Consequently our predictions could serve as a rather severe test of the basic theory. Alternatively, if we have confidence in the theory, our predictions could serve as a test of the reliability of total cross-section measurements. Since a number of high-energy hadron-nucleus total cross-section measurements have been made in recent years,[5] we have calculated these cross sections and compared them with the data. In addition, we have investigated the speed with which the multiple-scattering series "converges" by finding the number of terms of the series that must be retained in order to obtain a numerically accurate result. Lastly, we have calculated the ratios of the real to imaginary parts of hadron-nucleus forward elastic scattering amplitudes, quantities which are of importance in analyses of the contribution of the interference between Coulomb and nuclear elastic amplitudes to the measured total cross sections. A more detailed presentation of our investigations and results will be given elsewhere.

The amplitude for collisions in which the nucleus makes a transition from an initial state i to a final state f and has momentum $\hbar q$ imparted to it may be written[1,6]

$$F_{fi}(\vec{q}) = (ik/2\pi)\int e^{i\vec{q}\cdot\vec{b}}\langle f|[1-e^{i\chi_{\text{tot}}(\vec{b},\vec{r}_1,\cdots,\vec{r}_A)}]|i\rangle d^2b, \tag{1}$$

where $\hbar k$ is the momentum of the incident hadron, $\vec{r}_1, \cdots, \vec{r}_A$ are the coordinates of the target nucleons, and χ_{tot} is a phase-shift function. The integration is over the plane of impact-parameter vectors $\vec{b}$