APPENDIX I

Summary of the Experimental Limitations On The Muon Decay Hamiltonian

The fact that the measurable properties of muon decay cannot by themselves specify the muon decay hamiltonian has been stated in the introduction. The ambiguities which exist make it impossible to make a precise interpretation of this experiment unless a few additional restrictions are imposed on the hamiltonian. There are two assumptions that can be made, seemingly self-evident, to help restrict the possible interpretations of the experiment. A reasonable first assumption is to treat muon decay as a weak interaction, since one of the reasons for studying muon decay is to measure the bare weak interaction coupling constants. The second assumption made is that the weak interaction hamiltonian in the limit of low momentum transfer is properly represented by a current-current interaction. A consequence of these two assumptions is that the properties of the lepton currents can be established by decay processes other than muon decay.

The purpose of the following analysis is to make plausible restrictions on the muon decay hamiltonian and then finally to set a limit on η. The starting point for the computation of η is a phenomenological hamiltonian of the form:

$$
\begin{aligned}
H_I(x) = {} & G_S\tilde{\mu}(1+a_\mu^S i\gamma_5)\nu_\mu\tilde{\nu}_e(1-a_e^S i\gamma_5)e \; + \\
& G_V\tilde{\mu}\gamma_\alpha(1+a_\mu^V i\gamma_5)\nu_\mu\tilde{\nu}_e(1-a_e^V i\gamma_5)\gamma_\alpha e \\
& G_T\tilde{\mu}\sigma_{\alpha\beta}(1+a_\mu^T i\gamma_5)\nu_\mu\tilde{\nu}_e(1-a_e^T i\gamma_5)\sigma_{\alpha\beta} e
\end{aligned}
\qquad \text{(AI-1)}
$$

In order to use the formulae for ρ, η, ξ, and δ which appear in the literature it is necessary to reorder the fermion fields in (AI-1) to the order in Eq.(AI-2).

$$H_I(x) = \sum_{\ell=1}^{5} g_i \tilde{\mu}\Gamma_i e \tilde{\nu}_e \Gamma_i \nu_\mu - g_i^1 \tilde{\mu}\Gamma_i e \tilde{\nu}_e \Gamma_i i\gamma_5 \nu_\mu$$

$\Gamma_1 = 1 \qquad \Gamma_2 = \gamma_\alpha \qquad \Gamma_3 = \frac{i}{2\sqrt{2}} [\gamma_\alpha, \gamma_\beta] \qquad \Gamma_4 = i\gamma_\alpha\gamma_5 \qquad \Gamma_5 = -i\gamma_5$

Equations (AI-1) and (AI-2) are connected by a Fierz transformation which relates the G_S, G_V, G_T, a_μ^S, etc. to the g_i and g_i^1.

These hamiltonians, which are equivalent, are the most general which are consistent with a point interaction without derivative coupling. The relationship between Eqs. (AI-1) and (AI-2) is given by the following ten equations.

$$g_1 = G_V(1-a_e^V a_\mu^V) + \frac{3G_T}{\sqrt{2}}(1-a_T^e a_T^\mu) + \frac{G_S}{4}(1-a_e^S a_\mu^S) \qquad \text{(AI-3)}$$

$$g_2 = -\frac{G_V}{2}(1+a_\mu^V a_e^V) + \frac{G_S}{4}(1+a_e^S a_\mu^S) \qquad \text{(AI-4)}$$

$$g_3 = \frac{G_T}{2}(1-a_e^T a_\mu^T) + \frac{\sqrt{2}}{8} G_S(1-a_e^S a_\mu^S) \qquad \text{(AI-5)}$$

$$g_4 = -\frac{G_V}{2}(1+a_\mu^V a_e^V) - \frac{G_s}{4}(1+a_e^S a_\mu^S) \qquad \text{(AI-6)}$$

$$g_5 = -G_V(1-a_\mu^V a_e^V) + \frac{3G_T}{\sqrt{2}}(1-a_e^T a_e^T) + \frac{G_S}{4}(1-a_e^S a_\mu^S) \qquad \text{(AI-7)}$$

$$g_1' = \left\{ G_V(a_\mu^V - a_e^V) + \frac{3G_T}{\sqrt{2}}(a_\mu^T - a_e^T) + \frac{G_S}{4}(a_\mu^S - a_e^S) \right\} \quad \text{(AI-8)}$$

$$g_2' = \left\{ -\frac{G_V}{2}(a_\mu^V - a_e^V) + \frac{G_S}{4}(a_\mu^S + a_e^S) \right\} \quad \text{(AI-9)}$$

$$g_3' = \left\{ -\frac{G_T}{2}(a_\mu^T - a_e^T) + \frac{G_S\sqrt{2}}{8}(a_\mu^S - a_e^S) \right\} \quad \text{(AI-10)}$$

$$g_4' = \left\{ -\frac{G_V}{2}(a_\mu^V + a_e^V) - \frac{G_S}{4}(a_\mu^S + a_e^S) \right\} \quad \text{(AI-11)}$$

$$g_5' = \left\{ -G_V(a_\mu^V - a_e^V) + \frac{3G_T}{\sqrt{2}}(a_\mu^T - a_e^T) + \frac{G_S}{4}(a_\mu^S - a_e^S) \right\} \quad \text{(AI-12)}$$

The order of the lepton fields in the mu-decay hamiltonian is a consequence of the absence of neutral currents. The order most commonly found in the literature, the charge retention order (Eq.(AI-2) is not found in nature. In the case of a pure V-A interaction one order transforms into the other. Experimentally, only charged lepton currents have ever been observed, (Eq. AI-1), as will be shown in the following review of experiments. The leptonic current is believed to be

$$\ell_\alpha(x) = \tilde{\mu}\gamma^\alpha(1+i\gamma_5)\nu_\mu + \tilde{e}\gamma^\alpha(1+i\gamma_5)\nu_e + \text{H.C.} \quad \text{(AI-13)}$$

All experiments done to date require that the currents have $\Delta Q = \pm 1$. The presence of neutral lepton currents in the weak interaction hamiltonian would give to rise to terms such as

$$\frac{g_{\mu e} g_{NN}}{\sqrt{2}} \left[\tilde{p}\gamma_\alpha(1+i\gamma_5)p + \tilde{n}\gamma_\alpha(1+i\gamma_5)n\right] \tilde{\mu}\gamma^\alpha(1+i\gamma_5)e \quad \text{(AI-14)}$$

$$\frac{g_{\mu e} g_{ee}}{\sqrt{2}} \left[\tilde{\mu}\gamma_\alpha(1+i\gamma_5)e\ \tilde{e}\gamma^\alpha(1+i\gamma_5)e\right] \quad \text{(AI-15)}$$

$$g_{\mu\mu} G_T \frac{\partial K_{o2}}{\partial x^\alpha} \tilde{\mu}\gamma^\alpha(1+i\gamma_5)\mu + g_{ee} G_T \frac{\partial K_{o2}}{\partial x^\alpha} \tilde{e}\gamma^\alpha(1+i\gamma_5)e \quad \text{(AI-16)}$$

The first of these terms, Eq.(AI-14), would give rise to the process

$$\mu^- + N(A,Z) \rightarrow e^- + N^*(A,Z) \quad . \qquad \text{(AI-17)}$$

N(A,Z) is a nucleus of atomic number A and charge Z. $N^*(A,Z)$ is a collection of A nucleons of which Z are charged. The experimental upper limit of the process is 2.5×10^{-7} times smaller than the allowed process[40] given by Eq.(AI-17).

$$\mu^- + N(A,Z) \rightarrow \nu_\mu + N^*(A,Z-1) \quad . \qquad \text{(AI-18)}$$

Hence a lower limit on $g_{\mu d} g_{nn}$ may be established as $g_{\mu e} g_{nn} < 5 \times 10^{-4}\ G_f$.

Similarly, the term of Eq. (AI-15) would give rise to the decay mode of the μ-meson.

$$\mu^+ \rightarrow e^+ + e^- + e^- \quad . \qquad \text{(AI-19)}$$

The branching ratio of this mode to the decay mode $\mu^+ \rightarrow e^+ + \bar{\nu}_r + \nu_e$ is less than 1.5×10^{-7},[41] consequently, $g_{\mu e} g_{ee} < 4 \times 10^{-4}\ G_f$. Both of these processes could also occur if ν_μ and ν_e were the same through electromagnetic interactions. The most direct experimental evidence for the lack of neutral currents is their absence in K_{o2} decay. If a neutral current existed then using the term Eq.(AI-16) in the decay hamiltonian the rate

$K_{o2} \rightarrow \mu^+ + \mu^-$ to $K^+ \rightarrow \mu^+ + \nu_\mu$ would be [42]

$$\frac{R(K_{o2} \rightarrow \mu^+ + \mu^-)}{R(K^+ \rightarrow \mu^+ + \nu)} = \frac{|g_{\mu\mu}|^2}{G_f} \frac{m_K^{\ 3} (m_K^{\ 2} - 4m_\mu^{\ 2})^{1/2}}{(m_K^{\ 2} - m_\mu^{\ 2})^2} = \frac{|g_{\mu\mu}|^2}{G_f} \qquad \text{(AI-20)}$$

the branching ratio $K_{o2} \rightarrow \mu^+ + \mu^-$ to all modes of K_{o2} decay is experimentally known[43] to be less than 10^{-4}.

$$(g_{\mu\mu})^2 < 5 \times 10^{-5} G_f$$

Moreover, neutral currents if present would be detected by the K^+ decay into $\pi^+e^+e^-$, $\pi^+\mu^+\mu^-$ or $\pi^+\bar{\nu}\nu$. The experimental limit[44] on the branching ratio of the $\pi^+e^+e^-$ to all K^+ decay modes is 2.5×10^{-6}. These modes have not been observed, and this fact reinforces the above conclusion.

The current written in Eq.(AI-13) satisfies conservation of leptons and muons. Muon conservation was first established directly in the high energy neutrino experiments. In the experiments done by the Columbia group and the CERN group, it was found that the process[45,46]

$$\nu_\mu + N(A,Z) \rightarrow N^*(A,Z+1) + e^- \qquad \text{(AI-21)}$$

occurred at a rate which was less than 1% of the rate of the allowed process.

$$\nu_\mu + N(A,Z) \rightarrow N^*(A,Z+1) + \mu^- \; . \qquad \text{(AI-22)}$$

ν_μ is the neutrino from the decay of the positive pion. The result of this experiment is interpreted as the fact that the neutrino from π-decay is different from the neutrino from nuclear β-decay. Indirect evidence for the conservation of muon number comes from the absence of the decay $\mu \rightarrow e + \gamma$. The branching ratio of this decay mode has been measured to be less than 2×10^{-8}.[47] An estimate of the rate for this process in the intermediate boson theory by Feinberg gave branching ratio of[48]

$$\frac{R(\mu \rightarrow e + \gamma)}{R(\mu \rightarrow e\nu\bar{\nu})} \approx \left(\frac{\alpha}{24\pi}\right) N^2 \qquad \text{(AI-23)}$$

where N is a logarithmically diverging constant of order 1.

T.D. Lee pointed out that the non-locality does not need to be provided by a vector boson, since higher order weak interactions will provide such a non-locality. Furthermore, one obtains a result which is comparable to Feinberg's if one uses for a cutoff in the calculation of these divergent processes the unitary limit of weak interactions. In the spirit of the proceeding estimates of coupling constants, the experimental upper limit of $|g_{\mu\nu_e}|^2$ or $|g_{e\nu_\mu}|^2$ would be 10% to 1% of G_f, depending on the interpretation of the $\mu \rightarrow e + \gamma$ result.

Surprisingly enough the conservation of leptons as an independent conservation law is not so well established. The CERN neutrino experiment placed an upper limit of 6% on the lepton non-conserving processes.[45] The lepton violating amplitude can be as large as 25%.

In addition to the lack of neutral currents the next most strongly established absence of a property of the lepton current is the absence of a fundamental scalar and pseudoscalar current. All experiments are consistent with ℓ_α transforming as a vector under proper lorentz transformations. While many experiments are also consistent with a 10% admixture of pseudoscalar coupling there are two important exceptions. The ratio of the decay rate of the π into an electron and a neutrino to the rate for decay into a muon and a neutrino is very sensitive to the presence of a slight admixture of either scalar or pseudoscalar coupling. A similar result is true for the ratio of the same decay modes for the K meson. This ratio has been measured for π-decay and is[11]

$$\frac{R(\pi^+ \to e^+ + \nu)}{R(\pi^+ \to \mu + \nu)} = 1.23 \times 10^{-4} \pm 0.02 \ .$$

The agreement with a V-A theory is within the experimental error. If this result is used to put an upper limit on the presence of a term like Eq.(AI-24) in the π-decay hamiltonian

$$G_\pi G_s \pi \left[\frac{\tilde{\mu}(1+i\gamma_5)\nu_\mu}{2} + \frac{\tilde{e}(1+i\gamma_5)\nu_e}{2} \right] \qquad \text{(AI-24)}$$

Then the magnitude of G_S must satisfy the following inequality

$$G_s{}^2 < \left(\frac{2\times 10^{-6}}{5} \right) G_f{}^2 = 4 \times 10^{-7} \ G_f{}^2 \ .$$

The observation of K_{e2} decay has only been done recently and the branching ratio based on three events is consistent with the result predicted by the V-A theory. The value of G_S derived from β-decay is less than 0.01 G_V. This result follows from the absence of pseudoscalar coupling in β-decay.[37]

The limit on the tensor coupling is not as well-established as the case for the scalar coupling; nevertheless, some evidence exists in β-decay and K^+-decay. From form factors of K^+_{e3} and $K^+_{\mu 3}$ decay the value of $G_T < 0.3\ G_V$.[49] From β-decay G_T must be less than 0.1 G_V.[50]

Much better restrictions may be placed on G_T by using the best results for the measurements of ρ, δ, and ξ, as will be shown. Using the relations between the coupling constants obtained in Eq. (AI-3) and (AI-12) and the formulae for ρ, δ, ξ and η given in Refs. 6 and 7, ρ, δ, ξ, and η can be written as

$$\rho = \frac{3}{2\Delta}\left\{G_V{}^2[(1+a_\mu^V a_e^V)^2 + (a_\mu^V+a_e^V)^2] + G_T^2[(1-a_\mu^T a_e^T)^2 + (a_\mu^T-a_e^T)^2]\right\} \quad \text{(AI-25)}$$

$$\delta = \frac{3[G_V{}^2(1+a_\mu^V a_e^V)(a_\mu^V+a_e^V)+G_T{}^2(1-a_\mu^T a_e^T)(a_\mu^T-a_e^T)]}{G_V{}^2[-12(1-a_\mu^V a_e^V)(a_\mu^V-a_e^V)+4(a_\mu^V+a_e^V)(1+a_\mu^V a_e^V)]-47G_T{}^2(1-a_\mu^T a_e^T)(a_\mu^T-a_e^T)} \quad \text{(AI-26)}$$

$$\xi = \frac{-G_V{}^2}{\Delta}[-12(1-a_\mu^V a_e^V)(a_\mu^V-a_e^V)+4(a_\mu^V+a_e^V)(1+a_\mu^V a_e^V)]+47G_T{}^2(1-a_\mu^T a_e^T)(a_\mu^T-a_e^T) \quad \text{(AI-27)}$$

$$\eta = \frac{\frac{12}{\sqrt{2}}G_V G_T}{\Delta}[(1-a_e^T a_\mu^T)(1-a_e^V a_\mu^V)+(a_\mu^V-a_e^V)(a_\mu^T-a_e^T)] \quad \text{(AI-28)}$$

$$\Delta = 2G_V{}^2[(1-a_\mu^V a_e^V)^2+(a_\mu^V-a_e^V)^2+(1+a_\mu^V a_e^V)^2+(a_\mu^V+a_e^V)^2] + \frac{21}{2}G_T{}^2[(1-a_\mu^T a_e^T)^2+(a_\mu^T-a_e^T)^2] \quad \text{(AI-29)}$$

This form is not entirely useful. A more useful form would use the hamiltonian

$$\mathcal{H} = \sqrt{8}G_V'\tilde{\mu}\gamma_\alpha\left[\frac{(1+i\gamma_5)}{2}+\alpha_\mu^V\frac{(1-i\gamma_5)}{2}\right]\nu_\mu\tilde{\nu}_e\left[\frac{(1-i\gamma_5)}{2}+\alpha_e^V\frac{(1+i\gamma_5)}{2}\right]\gamma_\alpha e + \sqrt{8}G_T'\tilde{\mu}\sigma_{\alpha\beta}\left[\frac{(1+i\gamma_5)}{2}+\alpha_\mu^T\frac{(1-i\gamma_5)}{2}\right]\nu_\mu\tilde{\nu}_e\left[\frac{(1-i\gamma_5)}{2}+\alpha_e^T\frac{(1+i\gamma_5)}{2}\right]\sigma_{\alpha\beta}e \quad \text{(AI-30)}$$

The relations between the G's of Eq.(AI-1) and Eq.(AI-30) are given by

$$(G_V') = \frac{(G_V)}{(1+\alpha_\mu^V)(1+\alpha_e^V)} \qquad \alpha_\mu^V = \frac{1-a_\mu^V}{1+a_\mu^V} \qquad \alpha_e^V = \frac{(1-a_e^V)}{(1+a_e^V)} \quad \text{(AI-31)}$$

$$(G_T') = \frac{G_T}{(1+\alpha_\mu^T)(1+\alpha_e^T)} \qquad \alpha_\mu^T = \frac{(1-a_\mu^T)}{(1+a_\mu^T)} \qquad \alpha_e^T = \frac{(1-a_e^T)}{(1+a_e^T)} \quad \text{(AI-32)}$$

Writing the hamiltonian in this way the components of the majorana neutrino which would violate lepton conservation are proportional to one of the α's. The formulae for ρ, δ, ξ, and η then

$$\eta = \frac{\frac{6}{\sqrt{2}}\left(\frac{G'_T}{G'_V}\,\alpha^T_\mu \alpha^V_\mu + \frac{G'_T}{G'_V}\,\alpha^T_e \alpha^V_e\right)}{\left(1+(\alpha^V_\mu)^2+(\alpha^V_e)^2+(\alpha^V_\mu \alpha^V_e)^2+\frac{21}{4}\left[\left(\frac{G'_T}{G'_V}\,\alpha^T_\mu\right)^2+\left(\frac{G'_T}{G'_V}\,\alpha^T_e\right)^2\right]\right)} \tag{AI-33}$$

$$\xi = -\frac{\left(1-3\left[(\alpha^V_e)^2-(\alpha^V_\mu)^2\right]-(\alpha^V_\mu \alpha^V_e)^2-\frac{47}{4}\left[\left(\frac{G'_T}{G'_V}\,\alpha^T_e\right)^2-\left(\frac{G'_T}{G'_V}\,\alpha^T_\mu\right)^2\right]\right)}{\left(1+(\alpha^V_\mu)^2+(\alpha^V_e)^2+(\alpha^V_\mu \alpha^V_e)^2+\frac{21}{4}\left[\left(\frac{G'_T}{G'_V}\,\alpha^T_e\right)^2+\left(\frac{G'_T}{G'_V}\,\alpha^T_\mu\right)^2\right]\right)} \tag{AI-34}$$

$$\delta = \frac{3}{4}\,\frac{\left(1-(\alpha^V_\mu \alpha^V_e)^2+\left(\frac{G'_T}{G'_V}\,\alpha^T_e\right)^2-\left(\frac{G'_T}{G'_V}\,\alpha^T_\mu\right)^2\right)}{\left(1-3\left[(\alpha^V_e)^2-(\alpha^V_\mu)^2\right]-(\alpha^V_\mu \alpha^V_e)^2-\frac{47}{4}\left[\left(\frac{G'_T}{G'_V}\,\alpha^T_e\right)^2-\left(\frac{G'_T}{G'_V}\,\alpha^T_\mu\right)^2\right]\right)} \tag{AI-35}$$

$$\rho = \frac{3}{4}\,\frac{\left(1+(\alpha^V_\mu \alpha^V_e)^2+\left(\frac{G'_T}{G'_V}\,\alpha^T_e\right)^2+\left(\frac{G'_T}{G'_V}\,\alpha^T_\mu\right)^2\right)}{\left(1+(\alpha^V_\mu)^2+(\alpha^V_e)^2+(\alpha^V_\mu a^V_e)^2+\frac{21}{4}\left[\left(\frac{G'_T}{G'_V}\,\alpha^T_e\right)^2+\left(\frac{G'_T}{G'_V}\,\alpha^T_\mu\right)^2\right]\right)} \tag{AI-36}$$

In this form there are only four independent parameters, α^V_μ, α^V_e, $\frac{G'_T\alpha^T_\mu}{G'_V}$, and $\frac{G'_T}{G'_V}\,\alpha^T_e$. The analysis of β-decay experiments can be used to set limits of $(\alpha^V_e)^2 < 0.01$, $(\frac{G_T}{G_V}\,\alpha^T_e)^2 < 0.01$.

By using the best experimental values for ξ and δ,[12,13] the limits on $\frac{G_T'}{G_V'}\alpha_\mu^T$ and α_μ^V can be set as follows:

$$|\alpha_\mu^V| < 0.2 \qquad\qquad |\frac{G_T'}{G_V'}\alpha_\mu^T| < 0.02$$

As a result η can be restricted to $\eta < 0.04$.

APPENDIX II

Sonic System Electronics

The sonic data unit can be used to measure a variety of experimental data. These include measurement of sonic transit times to ± 0.2 μsec, decay times of muons to ± 10 nsec, and pulse heights of fast counter pulses. In all cases three features are retained: the experimental information which is inthe form of a set of pulses is converted to a time interval; the time interval is scaled by a crystal-controlled oscillator and stored on a set of four-decade BCD scalers; at the conclusion of each event all the data in the scalars are transmitted to the memory of a 1401 computer and then recorded on magnetic tape.

The sonic data system is composed of a 1401 computing system and a sonic data unit. The sonic data unit is made up of the following electronic units:

a) Eight or more digitron chasses

b) A main pulse generator chassis

c) A 1401 control chassis

d) A main control chassis.

These units are described in detail in the following paragraphs. A brief description of the 1401 system is also included.

A. Digitron Chassis Description

The digitron chassis accepts pulses from the experiment electronics and converts this information to digital data under the control of the main pulse generator. Several types of these units have been built, a list of which is given below:

1. Sonic transit time digitron (5 Mc)
2. 100 Mc digitron
3. Scintillation counter pulse height analyzer
4. Counter hodoscope register.

In each case the data are converted to digital form and stored on the four-decade BCD scales. The means by which the data are formed depend to some extent on the particular application. The sonic transit time digitron chassis which was the original unit constructed is described here. A block diagram of this is shown in Fig. 24.

The microphone pulse is amplified by a factor of 1000 in an amplifier, the band pass of which is matched to the microphone. The amplified signal varies from 0.25 volts to 5 volts depending on how far the spark was from the microphone. The amplified pulse triggers a discriminator which in turn resets the time interval flip-flop.

Since the rise time of the amplified microphone pulse is 1 μsec, it is necessary to compensate for the variation in the pulse height. This can be done simply by using an exponentially decaying discriminator bias since the smallest pulses arrive last. The pulse height actually varies inversely with time, as shown in Fig. 25. The amplifier is a narrow band pass amplifier passing frequencies from 100 kc to 2 Mc. Outside these limits the rejection is 6 dB per octave. The band width is matched to the resonant frequency of the lead-zirconate microphone.

The time interval flip flop is set by the start gate pulse, a 2-msec pulse delayed by 60 μsec from the instant the spark chambers are fired. The time interval flip-flop if reset by the output of the time interval discriminator and the time interval flip-flop cannot be set again until a new start gate is generated. During the time interval between set and reset a 5.0 Mc oscillator is gated into each four-decade scaler. A block diagram of the scaler is shown in Fig. 37. After the start gate has ended, the main control chassis, the 1401 control chassis, and the 1401 computer control the flow of the data from the scalers by activating chassis and channel select lines located in the digitron chassis. The four digits of a channel are mixed with corresponding digits of the other three channels. The mixed sixteen lines of output are sent to the main control chassis. The code of the scalers is given in Table XV below.

TABLE XV

BCD Code of Decade

Digit	One Line	Two Line	Four Line	Two Prime Line
0	0	0	0	0
1	X	0	0	0
2	0	X	0	0
3	X	X	0	0
4	0	0	X	0
5	X	0	X	0
6	0	X	X	0
7	X	X	X	0
8	0	X	X	X
9	X	X	X	X

This is not the scheme used by the 1401 or the Hewlett-Packard printer. Decoding for these units is done in the main control chassis.

B. Main Pulse Generator Description

With the exception of the trigger amplifier the circuits of the main pulse generator are made from the Nevis slo-logic univibrators, Dwg. No. B30504 and gates, Dwg. No. B2656. The main pulse generator chassis generates pulses which are used to reset all flip-flops, counters, and gate discriminators off during the time which the electrical noise generated by the sparks comes into the sonic data unit. The noise presented a serious problem since complete shielding was not possible. For this reason the noise was considered omnipresent and the logic of the processing was arranged to be independent of its presence.

The main pulse generator block diagram is shown in Fig. 38. The main pulse generator generates three pulses after receiving an input trigger pulse. These pulses are:

1. Reset Pulse - the duration is 50-μsec and is generated promptly from the amplified trigger pulse. The reset pulse is fanned out and sent to each digitron chassis, the 1401 control chassis, and main control chassis. The reset pulse, generated by a univibrator, resets all BCD scalers and flip-flops.
2. Amplifier Gate - the pulse has a duration of 2.0 msec and is generated promptly by a univibrator. The

negative amplifier gate is used to gate the last stage of the digitron amplifier on. The pulse is fanned out eight times in the main pulse generator chassis and sent to each digitron chassis.

3. Start Gate - this pulse has a length of 2 msec and is delayed by 60 μsec. It is generated by making an anticoincidence with the positive amplifier gate and a pulse of 60-μsec duration. Since the leading edge of the start gate is the time with respect to which the sonic transit time intervals are measured, the 60-μsec delay must be generated accurately. The pulse is delayed so that the transit times are measured after the electrical noise due to the spark has decayed to a negligible value. This noise is conducted into the system on the cables which are attached to the microphones from the transducers. It is more than ten times the signal from the sound wave. If scaling were done immediately this noise would cause the clocks to be stopped during the first 10 μsec. The 60 μ-sec pulse is generated by triggering a univibrator with a 100-μsec output pulse. The univibrator pulse is then used to gate a 5-Mc oscillator which drives a four decade scaler of the type described in Fig. 37. When it has counted to 300 the counter output is used to inhibit the 100-μsec univibrator pulse. The scaled 60-μsec pulse is put in anticoincidence with the amplifier gate, thereby generating

the start gate. Because this four-decade scaler can be isolated from the electrical noise, the scaling is not affected. Finally, it is to be noted that the delay is measured with a 5-Mc oscillator which has the same phase as the oscillators for the time intervals, so that this delay does not introduce an additional least count error.

In addition to the aforementioned pulses, the main pulse generator generates the 5-Mc clock signal. This is done first by clipping and then amplifying the output of a 10-Mc crystal oscillator. This output is then scaled down to 5-Mc by driving a flip-flop. The output of the flip-flop is then fanned out eight times and sent to each digitron chassis, where it is reshaped and fanned out four more times to each channel. A block diagram of the main pulse generator is shown in Fig. 38.

C. The Main Control Chassis

The sixteen digit lines coming from each chassis are brought into the main control chassis and then connected together through diodes, a given digit line of all chasses is connected to a common point. The summed digit line pulses are amplified and the sixteen lines are reduced to four lines by combining the corresponding digit of each decade. The block diagram of these circuits is shown in Fig. 39 for the one line. The way in which the digits are sequenced is controlled in the following way. A step sequencer output is generated. The exact way in which the pulse is generated depends on which mode of operation the data unit is in. The only mode which is pertinent to the discussion is the computer mode. Digit sequencing is obtained by driving two flip-flops in series, as shown in Fig. 40. The digit sequencing then drives a set of two flip-flops for the channel select sequencing. The output of the channel select is used to drive three flip-flops which generate the chassis select pulses. The channel select pulses are fanned out eight times and sent to each chassis. The output of the third or last flip flop is used to generate the end of transmission pulse, which is sent to the 1401 control chassis. The select pulse logic is shown in Fig. 41.

D. The 1401 Control Chassis

This chassis controls the flow of data from the BCD scalers to the 1401 memory. A block diagram of it is shown in Fig. 37.

1. The logic for generating the step sequences pulse;
2. A decoder of the 1242 BCD code to a 1248 BCD code; the generation of a parity bit and the drivers for the lines to the 1401.
3. An end of transmission pulse circuit.

The 1401 must provide a I/O Read Call level during data transmission. The I/O Read Call is generated by the 1401 program when the 1401 is ready to read data. When the read call is on,an end-of-time pulse is generated by differentiating the trailing edge of the amplifier gate pulse. The scalers at this time are no longer counting, hence data can be transmitted to the 1401. The end-of-time pulse sets the 1401 control flip-flop, which in turn activates both the 1401 service request line and the step sequencer line. When a service request is generated, the 1401 senses it and reads the data on the data lines into the memory of the 1401. After this is done the following occurs:

a) Advances the location at which the next event will be stored,

b) Sends one clock pulse of 000-090 time,

c) Stops the program until it senses a service request, it is ready to read.

The 090-000 pulses inhibit the service request for 2.8 μsec and at the same time generate step-sequencer pulses, as shown in Fig. 26. This causes the next digit to be placed on the data lines. When the 000-090 pulse is gone the service request comes back on and the 1401 then reads the data lines again. The procedure is repeated until an end-of-transmission pulse is sensed. There are two end-of-transmission pulses, the first one is sent promptly after the trigger. The 1401 is programmed to recognize this as an end-of-transmission. The program simply transfers the data on the lines to a core storage location, stops after one digit, and awaits the arrival of a true service request at which time it reads the data into the core, writing over the noise digits. This added complication is necessary because from time to time a service request would be generated by noise and the data lines would be read promptly. The program would not differentiate this from a real service request and the subsequent digits would be stored in the wrong storage locations.

APPENDIX III

The Experimental Spectrum

A. Data Processing

The fact that 1.5×10^7 events had to be reconstructed made it necessary to use data processing techniques that are out of the ordinary routine encountered by physicists. An outline of the program used in the reconstruction sequence is given here.

The major problem in handling the data was to get data in the computer and in a form the computer could use in a reasonable amount of time. Fortran was entirely unsuitable for the operations which were performed. A data tape written by the 1401 contained tape records of 1536 BCD characters, which represented twelve events of 128 BCD characters. The 7094 is a binary machine which uses 36 Bit words and hence the data must be converted from BCD to binary. Of the 128 BCD characters only 80 contained useful information. The first program in the sequence edited the data tapes and wrote a binary output tape. Each event was read into the 7094 and converted to binary. Each four-digit BCD number was converted to 36 Bit words. The 48 BCD characters which contained no information were deleted. The event was then checked for identity with the previous event, identity with the same event of the previous record and more than one missing spark. If any of these conditions were satisfied the event was rejected and written on the rubbish tape at one event per record. The other events were assembled in core into records of 200 events in two separate categories. Events with one spark were written on one tape - the Missing Spark Tape, and events with no misses were written on another tape - Edited Data Tape. When the events were assembled for writing they were compacted into six 36 bit words. The number of tapes which had to be handled was reduced by a factor of five. The table below shows how many bits were given to each piece of information.

Channels 1 to 4	Chassis 1	12 Bits Per Channel
Channels 1 to 4	Chassis 2	13 Bits Per Channel
Channels 1 to 4	Chassis 3	13 Bits Per Channel
Channels 1 to 4	Chassis 4	13 Bits Per Channel
Channels 1 and 2	Chassis 5	14 Bits Per Channel
Channels 3 and 4	Chassis 7	9 Bits Per Channel

During the editing separate histograms were made of the events which missed each combination of chambers, and of the events which had the wrong record length or form.

After editing the Edited Data Tapes and the Missing Spark Tapes can be reconstructed. The Edited Data Tapes are reconstructed using a 7094 program. After each event is reconstructed the results of the calculation are truncated and stored. Table XVI gives a list of the quantities which are computed and the number of bits which are retained.

TABLE XVI

Information Stored on P' Tape

Variable	No. of Bits	Variable	No. of Bits
1	9	7	3
2	9	8	3
3	9	9	4
4	3	10	4
5	3	11	4
6	3		

Any of the 25 variables on the P tape could be assembled in the list of eleven variables appearing on the P' tape.

The final program in the data processing sequences was the histogram program. This program made a set of three-dimensional histograms; the number of histogram channels could not exceed 2^{15}. A unique feature of the program was the way in which the histogram was constructed. Each event was first tested to see whether it was in the outer limits of each variable; if accepted the first three variables were truncated and reassembled into a single 15 Bit number. This 15 Bit number corresponded to a particular address in the 7094 memory and hence a channel in the histogram. After computing the address, one was added to the contents of the address. The program had the virtue of being exceptionally fast and permitted the use of almost the entire memory for histograms. After all data had been read into the 7094 the contents of the memory were written on tape. The histogram tape was interpreted by a special 1401 program, which provided a set of one-dimensional histograms.

APPENDIX IV

Raw Data

The following histograms present the raw experimental data after angle selection criteria have been imposed. The limits of each variable are given in the first two lines of the table. The top line denotes the lower limit and the second line gives the upper limit. The limits are given in terms of binary numbers. The connection between the binary numbers and the decimal equivalents is as follows:

P		φ_T		α	
0	15 MeV	0	-55°	0	-7.5°
511	55 MeV	511	$+35^{\circ}$	511	$+7.5^{\circ}$

X_T		Z_T		Z_{IV}	
0	+4 cm	0	+4 cm	0	-15 cm
7	-4 cm	7	-4 cm	7	+15 cm

DZ4		PH2		DZ3	
0	-2 MeV/c	0	0	0	-2 MeV/c
7	+2 MeV/c	7	9999	7	+2 MeV/c

PHI		DR4	
1	0.045 MeV	0	-2 MeV/c
12	0.54 MeV	7	+2 MeV/c

The variables are listed from left to right as follows: P, φ_T, α, X_T, Z_T, Z_{IV}, DZ4, PH2, DZ3, PHI and DR4. The histograms list the experimental population for momentum intervals of 40/512 MeV/c.

MOMENTUM HISTOGRAM No. 1

Lower and Upper Limits

0	0	90	192	0	0	0	2	0	6	1	6
9999	511	300	319	7	7	7	5	7	9	12	9

78,472 Total Events 18,333 Total in Histogram 0 Also Total in Histogram

120	0	0	0	0	0	0	1	0	0	0
130	2	2	2	1	2	1	4	0	4	4
140	0	9	5	2	3	6	5	6	2	4
150	8	6	7	7	7	8	13	7	7	12
160	5	10	9	9	11	13	15	11	11	12
170	18	13	13	15	13	18	17	15	24	13
180	19	21	12	19	18	26	17	19	23	21
190	28	35	23	19	28	28	28	27	38	28
200	42	34	28	34	34	36	25	38	40	24
210	36	37	38	31	36	34	37	53	37	34
220	46	51	46	44	38	41	36	31	42	40
230	50	56	44	43	59	49	43	44	47	54
240	53	46	53	40	52	53	46	55	42	51
250	63	40	48	48	51	58	69	63	73	58
260	49	49	46	54	64	62	56	61	61	64
270	54	53	65	65	45	61	48	50	53	64
280	64	68	56	56	71	53	82	44	76	57
290	65	72	53	68	54	53	55	56	64	45
300	69	53	59	67	60	67	65	59	50	72
310	80	67	63	67	81	60	66	78	65	62
320	72	58	66	61	65	59	68	56	79	62
330	64	67	67	56	79	58	68	75	55	61
340	76	71	59	66	59	71	72	65	70	61
350	61	69	60	62	67	80	72	73	91	63
360	63	65	62	64	71	64	62	67	72	73
370	65	66	71	60	66	76	61	69	66	63
380	78	68	65	54	69	65	70	85	65	77
390	70	76	64	59	60	64	66	68	78	61
400	70	69	66	78	92	74	42	72	61	72
410	83	86	77	68	77	74	58	70	65	77
420	79	56	76	74	73	69	79	74	68	78
430	75	62	67	67	71	62	67	80	78	61
440	69	90	70	88	78	88	64	59	82	77
450	66	77	73	59	58	67	71	74	64	69
460	61	66	62	79	67	71	69	64	64	71
470	60	85	61	72	69	74	62	50	53	56
480	64	49	31	13	10	4	3	0	1	0
490	1	0	0	0	0	0	0	0	0	0

For P Between 0 and 119 All Sums are Zero
Between 500 and 511 All Sums are Zero

1 P 512

18,333 Events in Above Histogram 512 Boxes in Above Histogram

7.2 kG

MOMENTUM HISTOGRAM No.2 - Lower and Upper Limits

0	0	90	192	0	0	0	2	0	6	1	6
9999	511	300	319	7	7	7	5	7	9	12	9

3,867,972 Total Events 986,150 Total in Histogram 0 also Total in Histo.

1 P 512 For P Between 0 and 79 all sums are Zero

80	0	2	3	3	7	13	18	18	20	30
90	35	47	44	47	58	59	75	77	81	97
100	105	115	119	127	151	167	185	185	213	224
110	233	227	267	254	294	293	340	315	369	325
120	372	396	419	426	432	474	453	534	561	517
130	616	594	586	615	638	677	710	710	719	844
140	808	779	800	906	955	879	993	1057	1016	1115
150	1123	1069	1095	1181	1222	1332	1292	1316	1373	1341
160	1335	1435	1481	1485	1508	1511	1602	1618	1624	1728
170	1728	1654	1709	1752	1886	1914	1934	1955	1948	1936
180	1973	1956	1976	1992	2078	2025	2029	2069	2136	2148
190	2159	2102	2173	2165	2245	2307	2207	2245	2273	2196
200	2214	2329	2279	2369	2287	2332	2325	2228	2329	2376
210	2384	2346	2408	2470	2438	2431	2418	2440	2463	2440
220	2568	2371	2517	2423	2536	2550	2487	2505	2549	2592
230	2550	2563	2613	2587	2449	2598	2568	2621	2634	2585
240	2683	2668	2605	2610	2690	2604	2690	2719	2708	2684
250	2738	2688	2784	2756	2848	2717	2619	2669	2832	2768
260	2750	2751	2864	2777	2737	2828	2879	2824	2716	2768
270	2859	2825	2893	2785	2935	2917	2857	2881	2942	2822
280	2854	2951	2839	2911	2916	2190	3001	2989	3047	2935
290	2931	2974	2928	3056	2891	2994	3026	3065	2983	3000
300	2954	3076	3043	3070	3116	3102	3078	3131	3129	3017
310	3089	3092	3049	3119	3148	3129	3128	3134	3040	3182
320	3317	3160	3129	2958	3115	3283	3263	3115	3210	3217
330	3242	3160	3156	3129	3235	3184	3246	3285	3265	3279
340	3248	3252	3194	3277	3148	3234	3194	3338	3229	3303
350	3154	3241	3227	3189	3323	3357	3384	3282	3355	3361
360	3293	3374	3259	3297	3320	3342	3321	3267	3383	3267
370	3381	3374	3251	3374	3402	3370	3332	3380	3338	3344
380	3395	3426	3339	3416	3479	3362	3405	3450	3509	3357
390	3337	3316	3368	3475	3383	3346	3453	3357	3499	3357
400	3363	3373	3470	3347	3355	3353	3454	3494	3504	3393
410	3464	3413	3426	3467	3465	3460	3331	3385	3402	3568
420	3392	3375	3427	3419	3452	3499	3446	3398	3439	3364
430	3382	3471	3391	3443	3416	3370	3542	3434	3381	3432
440	3394	3507	3425	3428	3326	3595	3468	3352	3468	3452
450	3402	3422	3454	3443	3510	3409	3409	3355	3386	3424
460	3405	3390	3413	3342	3235	3345	3419	3419	3360	3378
470	3372	3321	3250	3296	3257	3207	3148	3088	2946	2750
480	2458	1900	1255	670	373	180	94	31	21	12
490	8	1	0	3	2	1	0	0	1	0
500	1	0	0	0	0	0	0	0	0	0

For P Between 510 and 511 all sums are Zero

986,150 Events in Above Histogram 512 Boxes in Above Histogram

6.6 kG

MOMENTUM HISTOGRAM No. 3 - Lower and Upper Limits

0	0	90	192	0	0	0	2	0	6	1	6
9999	511	300	319	7	7	7	5	7	9	12	9

2,111,626 Total Events 614,524 Total in Histogram 0 also Total in Hist.

1 P 512 For P between 0 and 19 all sums are Zero

20	0	0	0	0	0	0	0	0	0	1
30	2	1	0	4	3	11	12	13	14	17
40	20	26	24	41	33	35	31	74	70	78
50	70	90	70	74	100	101	131	112	114	130
60	150	135	145	171	184	189	204	218	204	249
70	230	338	271	297	285	331	310	373	369	356
80	373	416	431	426	459	513	516	483	561	577
90	601	631	582	657	644	657	675	778	754	779
100	785	808	900	887	911	935	892	920	930	976
110	973	947	999	994	1103	1042	1070	1037	1032	1061
120	1139	1066	1205	1134	1294	1233	1189	1168	1159	1235
130	1183	1224	1206	1134	1187	1170	1322	1228	1296	1255
140	1238	1355	1284	1220	1324	1228	1265	1312	1335	1427
150	1343	1374	1357	1335	1369	1314	1342	1311	1340	1374
160	1366	1432	1343	1369	1359	1500	1452	1449	1379	1511
170	1418	1382	1407	1413	1425	1412	1481	1456	1542	1489
180	1509	1487	1476	1508	1508	1552	1534	1506	1582	1587
190	1577	1586	1632	1666	1542	1618	1509	1601	1644	1592
200	1635	1588	1576	1629	1603	1620	1569	1540	1640	1663
210	1653	1675	1727	1690	1721	1742	1665	1664	1752	1643
220	1675	1732	1677	1635	1774	1743	1689	1728	1881	1719
230	1816	1686	1689	1685	1785	1727	1721	1774	1693	1761
240	1788	1883	1826	1767	1838	1862	1842	1792	1853	1774
250	1861	1779	1817	1802	1871	1888	1872	1843	1873	1949
260	1839	1860	1857	1859	1801	1906	1912	1983	1886	1947
270	1809	1946	1920	1918	1983	1967	1908	1988	1958	1901
280	1910	1974	1960	2048	2072	2015	1950	1954	2040	2022
290	2075	1984	1988	1947	2014	1992	2079	2058	1952	1973
300	2015	2014	2047	2075	2022	2031	1978	2019	1981	2075
310	2016	2088	2117	2074	2092	2114	2120	2127	2132	2058
320	2066	2101	2076	2119	2160	2055	2236	2123	2206	2168
330	2135	2170	2157	2147	2198	2194	2144	2103	2098	2153
340	2165	2211	2213	2169	2081	2149	2305	2301	2165	2192
350	2236	2257	2202	2240	2194	2139	2113	2214	2200	2184
360	2273	2188	2206	2204	2216	2237	2222	2171	2340	2248
370	2291	2163	2192	2363	2292	2284	2266	2270	2277	2261
380	2402	2236	2306	2277	2237	2276	2320	2195	2249	2247
390	2236	2278	2191	2110	2111	2127	2160	2051	2070	2105
400	2018	1968	1959	1865	1920	1869	1868	1836	1788	1762
410	1800	1764	1699	1686	1662	1702	1589	1459	1482	1466
420	1445	1390	1390	1286	1308	1335	1232	1166	1073	1138
430	998	1073	957	947	991	878	873	893	802	819
440	765	753	756	697	622	653	578	534	491	463
450	458	392	369	332	324	286	265	225	199	183
460	149	140	115	93	81	57	67	46	33	28
470	26	27	19	14	9	6	4	5	0	1

For P Between 480 and 511 all sums are Zero

5.3 kG

Hist.
1
17
78
130
249
356
577
779
976
1061
1235
1255
1427
1374
1511
1489
1587
1592
1663
1643
1719
1761
1774
1949
1947
1901
2022
1973
2075
2058
2168
2153
2192
2184
2248
2261
2247
2105
1762
1466
1138
819
463
183
28
1

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FIGURE CAPTIONS

Fig. 1	Arrangement of Spark Chambers in the Experiment
Fig. 2	Shape of the momentum spectrum of $\rho = 3/4$, showing the useful momentum range at each field setting
Fig. 3	Photograph of 36-in. Cloud Chamber Magnet
Fig. 4	Location of Shim Coils in the 36-in. Cloud Chamber Magnet
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