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A Study Of A Multi-Wire Proportional Counter For Magnetic Spectrograph Focal Plane Detection

by

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ABSTRACT

A Study of a Multi-Wire Proportional Counter for Magnetic Spectrograph Focal Plane Detection

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A multi-wire proportional counter (MWPC) was designed and successfully tested along the focal plane of the Rice University 65 cm magnetic spectrograph. The MWPC, which utilized .002" diameter stainless steel wires, a .100" wire spacing, and a .250" gap length, had an active area of 1" x 12". Counter efficiency and spatial resolution were determined by comparing the MWPC to results obtained with a position-sensitive solid state detector. The MWPC was thus found to be at least 98% efficient in the detection of 6 MeV protons. The spatial resolution of about 3 mm was limited by the multiple scattering of the protons in the counter foils and gas.
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I. INTRODUCTION

A. A Survey Of Multi-Wire Proportional Counters (MWPCs)

The single wire cylindrical proportional counter has now been regarded a standard tool in the nuclear physics laboratory for several decades. Also, the use of proportional counters with a few counting wires is an old achievement. However, the multi-wire proportional counters (MWPCs) under consideration here are of a relatively new expanded design. As their name suggests, MWPCs may have planes of tens or even hundreds of equally spaced parallel counting wires. These grounded wires are positioned midway between two thin parallel metalized foils to which negative high voltage is applied. Counting gas is contained by thin entrance and exit foils. MWPC systems have now been under development and in use at Rice University for over three years. They have also been actively studied at other laboratories by several experimental groups.

1. Properties Of MWPCs
   a. High detection efficiency and high counting rate capability: MWPCs are capable of detecting minimum ionizing particles such as electrons and pions as well as lower energy protons, deuterons, etc. with efficiencies
of 99+%. The high counting rate, approaching \(10^5\) Hz per wire, is expected since the dead time of a typical MWPC is of the order of just a few hundred nanoseconds. By contrast, the dead time of a multi-wire spark chamber is of the order of a few milliseconds. The MWPC pulses are relatively fast, with rise and decay times typically 100 nanoseconds and one microsecond respectively.

b. Thinness of only a few mg/cm\(^2\): For example, .00025" silverized mylar, which may be used for both the high voltage foils and the gas foils, is only 0.8 mg/cm\(^2\) thick, and argon, a typical counter gas, has a density of 1.8 mg/cm\(^3\) at S.T.P. The spectrograph focal plane detector under consideration here has a thickness of only about 7 mg/cm\(^2\) when operated with iso-butane at .2 atm.

c. \(dE/dx\) linear response: Since the counter is operated in the proportional mode, the size of the pulse directly off a wire will be proportional to the energy lost by the ionizing particle in traversing the counter. This may permit particle identification in some cases, since different types of particles possess varying specific ionizations.
d. Construction of small to large active areas of reasonably arbitrary dimensions: This is perhaps the most attractive feature, in that the counter operating characteristics such as efficiency, spatial resolution, etc., do not appear to be related to the length of the wires or the number of wires. Other types of position-sensitive detectors, such as solid state detectors, suffer degradation of position linearity with increased length. This flexibility of design suits MWPCs to a wide variety of experimental situations, to be discussed later.

e. Spatial resolution capabilities: The spatial resolution of a MWPC is determined by the wire spacing. Resolution of about 2 mm is common with the conventional configuration, while resolution less than a mm may be achieved only by additional techniques, which are later discussed.

2. Problems Associated With MWPCs

a. Amplification of signals: The primary problem associated with MWPCs is the amplification of the relatively weak signals and the allocation of each one to a particular wire. For example, a relativistic electron or pion
may produce a signal of only a few millivolts, and a counter of the type used along the focal plane of a magnetic spectrograph may require accurate position information from more than 500 or so wires over a length approaching one meter. The amplification and readout system used at Rice University is of the modularized type and employs integrated circuit amplifiers for each wire (app. D).

The primary advantage of this system is that the same amplifier cards (fig. 6-4) may easily be exchanged among the different MWPC configurations for various applications. In fact, all Rice University MWPCs, although different in size and shape, have been designed to be compatible with the same electronics.

b. Construction uniformity: Another possible problem associated with MWPCs is construction uniformity, both for individual counters and for semi mass-produced counters. For example, the construction of just one MWPC may require a hundred or so meters of fragile wire (≤.002" in diameter) and several square meters of high voltage foils and machined fiberglass. A foil with large wrinkles or an irregular surface or a wire with a smaller than average radius of curvature somewhere on its surface
will create higher than average fields which may lead to high voltage breakdown phenomena. However, numerous MWPCs have been semi mass-produced and found to operate quite reliably and consistently.

3. MWPC Design Modifications For Special Purposes

As mentioned previously, the conventional MWPC consists of a single plane of equally spaced parallel wires positioned between two high voltage foils. By modifying this design, counters may attain certain operating characteristics unobtainable with the conventional configuration.

a. Multi-coordinate readout counters: By combining two MWPCs with orthogonal wire planes, a bi-dimensional readout is easily facilitated (fig. 1-1). The sequence is: high voltage foil, wire plane, high voltage foil, orthogonal plane, high voltage foil. Extensions to multi-dimensional readout are similarly possible.

b. Intermediate grid chambers: In some cases, especially when detecting minimum ionizing particles at high efficiencies, high voltage breakdown may occur before reaching an acceptable operation level. If an additional intermediate foil or grid is placed close to the wires,
Figure 1-1. Photograph of a MWPC with associated electronics for bi-dimensional readout
in the region where the equipotentials are still essentially parallel, one may increase the fields in the drift region (between the high voltage foil and the intermediate foil) while keeping the fields around the wires unchanged. The technique has been used previously with cylindrical proportional counters. The advantages include reduced operating voltage and also shortened resolving time, since the positive ions cease to influence the discharge as soon as they reach the intermediate grid. This technique has also been investigated with MWPCs. For example, in the detection of 5.9 KeV X-rays, voltages of only 3 KV on the intermediate grid and 4 KV on the external grid were necessary to provide the same amplification that would have required 10 KV on the external grid, if operated without the intermediate grid.

c. High spatial resolution detectors: The MWPC spatial resolution is determined by the wire spacing. However, reduced wire spacing requires increasingly greater high voltage which may become excessive enough to lead to breakdown. It has been calculated that the addition of an intermediate high voltage wire midway between each pair of counting wires will strengthen the field and thus allow comparable gas amplifications with less external
voltage. A counter of this type has been designed and tested at Rice University. The counter parameters are (see fig. 2-1) $L = 0.250''$, $s = 0.050''$, $s_{\text{intermediate}} = 0.050''$, and $d = 0.001''$. With an intermediate voltage of about .2 the external voltage, the counter operated quite well with the reduced .050" wire spacing when detecting 2 MeV electrons. For $s = 0.050''$, the counter did not function satisfactorily without the intermediate wires, as breakdown ensued.

4. MWPC Applications

The aforementioned MWPC properties, especially the properties of spatial resolution, multi-dimensional readout, and construction flexibility make MWPCs well suited for certain types of applications. Some of these include:

1) particle ray tracing 2) beam profile analyzers
3) anticoincidence counters 4) neutron detectors
5) gamma-ray detectors 6) large solid angle detectors
and 7) magnetic spectrograph focal plane detectors. The design and use of a MWPC focal plane detector in the Rice University 65 cm broad range magnetic spectrograph will be discussed throughout the remainder of this thesis.

The MWPC is a device well suited for use along the focal plane in a magnetic spectrograph: 1) It is thin
enough to detect lower energy particles. 2) It may be designed with an active area which is long enough to cover the entire length of the focal plane as well as tall enough to detect essentially all the scattered particles which are focused vertically. 3) Spatial resolutions approximate those attained with solid state detectors and photographic emulsions. 4) It conforms reasonably well to the shape of the focal plane. 5) Rapid alignment on the focal plane is facilitated. A discussion of the broad range magnetic spectrograph and several other focal plane detection systems are included in the following section.
B. The Broad Range Magnetic Spectrograph

1. General Considerations

High resolution charged particle magnetic spectrographs are an important part of the equipment of many laboratories engaged in the study of nuclear structure. They are especially useful because their high resolving power matches the narrow energy spread of beams from Van de Graaff accelerators which are frequently used in nuclear structure studies. The charged particle products of a nuclear reaction enter the spectrograph through a system of slits and, after passing through the magnetic field, are brought to a focus on a slightly curved focal plane (fig. 6-1). The magnetic rigidity $Br$ of a particle is given by

$$Br = \frac{p}{q},$$

where $B$ is the magnetic field, $r$ the radius of curvature of the path of the particle, and $p$ and $q$ the momentum and charge respectively.

The Rice University 65 cm broad range magnetic spectrograph is a typical high resolution spectrograph and is available for use with beams from the Rice University 12 MeV Tandem Van de Graaff accelerator. The term broad range emphasizes the large range in energy of the
different particle groups which can be focused simultaneously onto the focal plane. For example, if a particle with energy E is bent 90°, then similar particles with energies ranging from 0.5 E to 1.2 E may be detected along the approximately 1 meter long focal plane (fig. 6-1). The energy resolution $\Delta E/E$ is one part in $10^3$ for a well collimated beam and a thin target. In terms of distances, this corresponds to measurements made every mm along the focal plane.

2, Focal Plane Detection Techniques

Until a few years ago the only detector capable of recording simultaneously particle intensities at such close intervals and over such a large physical span has been the nuclear track plate (photographic emulsion). This method is very simple and precise but it has several disadvantages: 1) It does not provide the experimenter with any information during the course of the experiment. 2) The scanning of the plate is very slow and tedious. 3) Particle identification is sometimes difficult. 4) Results of the scanning sometime suffer from subjective errors. 5) In general, the data capture and analysis are in no way compatible with modern computer data processing techniques. For these reasons, and
others, attempts have been made recently to obtain the focal plane spectra by various electronic methods. Much encouraging work has been done utilizing spark chambers with various types of spark localizing techniques as well as position-sensitive solid state detectors.

A spark is located in a sonic spark chamber by measuring the time interval between the firing of the spark and the arrival of the sound wave at the end of the chamber where it is detected by a sensitive microphone. Sonic chambers typically have a large dead time. For example, the velocity of sound in neon, a typical spark chamber gas, is only 435 meters/second. Thus the dead time in a one meter chamber would be at least 3 milliseconds.

Allen, et al., reports the testing of a sonic spark chamber for a magnetic spectrograph with 6 MeV Cm$^{244}$ alpha particles and 5-9.5 MeV protons. A 28" x 1" proportional counter directly in front of the chamber triggered the firing of the high voltage plane. The spark chamber worked well only when the proportional counter was operational, i.e. numerous spurious events were recorded when the chamber was operated with a steady d.c. voltage. The counter efficiency was 90%
for the alpha particles. However, higher proportional counter voltages were required for the proportional counter to be 100% efficient for the protons. This high voltage caused spurious pulses to appear at the output of the proportional counter and led to spreading of the sparks. Efficiencies of only about 3% were obtained for the proton beams, yet a spatial resolution of 0.5 mm was achieved.

Hardacre, et al., reports use of a sonic spark chamber with the Rutherford Laboratory 100 cm 180° double focusing magnetic spectrometer. Using .0025 cm aluminum electrodes with a 0.86 cm separation, a spatial resolution of 0.9 mm fwhm was obtained for particles in oblique incidence of 57° to the electric field. The chamber was used in coincidence with a double scintillator telescope, which enabled particle identification and selection to be performed before triggering the high voltage planes. The system operated reliably at 50 counts/second at efficiencies differing from 100% by less than one part in $10^4$ along the entire length of the focal plane. The active area of the counter was 46 x 3.3 cm. Line spectra with good mass resolution were obtained for singly charged particles resulting from 30 MeV proton-induced reactions. An overall energy
resolution of 60 KeV was obtained for these particles. The maximum sparking rate of 50 counts/second was limited by the duty cycle and short pulse length of the linac. It was suggested that improvements in spatial resolution by a factor of two or so would probably result from the use of several sonic transducers (microphones) instead of just one.

Another sonic chamber which was used in a 180° magnetic spectrometer is described by Saudinos, et al.\textsuperscript{23} The chamber had a spatial resolution of 1.5 mm over a 22 cm length for reaction products from 15-30 MeV proton-induced reactions, with the particle tracks being inclined at approximately 30°. The counter was 99% efficient and operated well at 100 counts/second. The sparks were localized by the Charpak charge division method.\textsuperscript{24}

Another spark localization method which not only is very accurate but also allows higher counting rates involves magnetostrictive effects. Magnetostriction is a property which allows stress waves to travel along wires or thin ribbons made of magnetostrictive materials (e.g. Fe, Ni, Cr) in which the wires or ribbons are magnetized to a suitable bias level. By choosing the dimensions of the wire or ribbon small compared with the wave length of the generated pulse it is possible to
generate a pure longitudinal mode which travels with velocity

\[ V = (\text{Ed})^{1/2}, \]

where \( E \) is Young's modulus of elasticity and \( d \) is the density of the material. A sensor picks up the signal at the end of the wire or ribbon and the position of the spark is determined by the time delay technique as in sonic chambers. For example, the velocity of a pulse in nickel, which has a high coefficient of magnetization, is approximately 5000 meters/second. This is an order of magnitude greater than the velocity of sound in a sonic spark chamber, yet the spark localization is just as accurate. Magnetostrictive effects in spark chambers have generally been employed in two different ways. One may either make the actual wires of the chamber from magnetostrictive materials and have the spark strike them directly, or place a thin magnetostrictive ribbon in close proximity to the chamber wires and couple magnetically to them via the current pulse in the sparking chamber wires.

Giannelli, et al., describes the type of wire chambers in which the wires themselves are of the magnetostrictive material. 25, 26, 27) Spark position measurements
were made for distances of 10 cm and 63 cm. A gaussian fit to these position signals yielded a standard deviation of 16 nanoseconds which was equivalent to 0.1 mm in determining the spark position.

Perez-Mendez, et al., describes a wire spark chamber having a magnetostrictive delay line readout that was used in the elastic scattering of $\pi^-$ from $\nu$ at the Berkeley 184" Synchrocyclotron. The delay lines used were .004" x .020" nickel ribbons. The spark chamber with 1 mm wire spacing had a spatial resolution of 0.3 mm. In conjunction with an analyzing magnet forming a magnetic spectrometer, the spark chamber achieved better than 1% momentum resolution for $\pi^-$ in the range 200-320 MeV/c. The elastically scattered peak at 15° had a momentum spread equal to the $\pm 2\%$ spread of the incident beam. A similar chamber has been found useful for measuring the spatial profile of particle beams.

Another successful spark locating technique involves passing each spark chamber wire through a magnetic core. When a wire counts, the spark current pulse flips the ferrite core magnetic field. Between beam pulses, associated electronics scan the array of cores, determine which ones are set, store the locations in a computer, and then reset all cores. A magnetic spectrometer system
which used multi-wire spark chambers with ferrite core readout was used by Friedes, et al., in the scattering of 1 GeV protons from protons, carbon, and oxygen at Brookhaven.\textsuperscript{30,31} The spectrometer system, which had an energy resolution of 3 MeV fwhm, used four spark chambers in front of two $18^\circ$ bending magnets and four more chambers behind the magnets. The wire spacing used was .050" and the spatial resolution was measured to be .030" when operated at a voltage such that 50\% of the events had two adjacent cores set. The approximately one millisecond cleanup time for the spark chambers would have allowed, in principle, 100 events per Cosmotron beam pulse to be analyzed. However, due to lack of computer memory, only 70 events per beam pulse could be handled.

A very successful technique actually used in the Heidelberg broad range magnetic spectrograph employs an array of position-sensitive solid state detectors placed along the one meter long focal plane.\textsuperscript{32} The spectrograph energy resolution of 0.1\% required at least 1 mm spatial resolution which restricted the effective length of each detector to 5 cm. This yielded a position-dependent signal linear to within 1\%, and the resolution was better than 1 mm for particles of 10 MeV. Each detector produced two output signals. One was proportional to $E$,
the energy loss of the detected particle, and the other was proportional to the quantity Ex/L, where x is the distance from one end of the detector and L is the detector length. Because of the differences of range in the detectors of various types of particles (p, d, α etc.) it was possible to differentiate among them by simple pulse height discrimination of the E pulses. The position along the focal plane was obtained by dividing the Ex/L signal by the E signal electronically. An array of six detectors covering 30 cm of the focal plane was checked by a measurement of the reactions $^{27}$Al(d,α)$^{25}$Mg and $^{27}$Al(d,d') at $E_d$=10 MeV. The E signal distribution gave three distinct peaks corresponding to protons, deuterons, and alpha particles. Thus, three separate spectra could be observed independently by gating the position signal on the appropriately discriminated E signal. The line widths of 1.3 mm were comparable to those obtained with nuclear emulsion plates.
II. Theory Of MWPC Operation

A. MWPC Field Configurations And Cylindrical Proportional Counters

The operation of a MWPC can best be understood by calculating the electric field strengths within the active counter volume. Consider an infinite array of wires of diameter "d" and spacing "s" with distance "L" from the wires to the high voltage plane, as shown in fig. 2-1. Let the coordinate system be centered on some wire, and x and y are in and perpendicular to, respectively, the plane of the wires. For infinitely thin wires, the potential V is given by

\[ V = q \ln \left[ \sin^2 \left( \frac{\pi x}{s} \right) + \sinh^2 \left( \frac{\pi y}{s} \right) \right], \]

where q is the charge per unit length on the wires, which, by symmetry, is the same for all wires. q is a function of L, d, s, and the applied voltage \( V_o \) and is given by

\[ q = \frac{V_o}{2 \left[ \ln \sinh(\pi L/s) - \ln \sinh(\pi d/2s) \right]}. \]

Simplified formulae hold along the symmetry lines s=0, y=0, and x=s/2:
Figure 2-1. MWPC construction parameters

L = gap length
s = wire spacing
d = wire diameter

x,y indicate coordinate system used.
\[ V(0,y) = 2q \ln \sinh \left( \frac{y}{s} \right), \quad 2-3a \]
\[ V(x,0) = 2q \ln \sin \left( \frac{x}{s} \right), \quad 2-3b \]
\[ V(s/2,y) = 2q \ln \cosh \left( \frac{y}{s} \right). \quad 2-3c \]

Differentiating yields expressions for the electric field:

\[ E_y(0,y) = \frac{2q \pi}{s} \coth \left( \frac{\pi y}{s} \right), \quad 2-4a \]
\[ E_x(x,0) = \frac{2q \pi}{s} \cot \left( \frac{\pi x}{s} \right), \quad 2-4b \]
\[ E_y(s/2,y) = \frac{2q \pi}{s} \tanh \left( \frac{\pi y}{s} \right). \quad 2-4c \]

In the above expressions \( q \) is the total charge per unit length of wire, and it should be distinguished from the differential charge distribution. By differential distribution is meant the azimuthal charge per unit wire surface area.

For a typical MWPC, consider points \( x,y \) near the wires where both \( x,y \ll s \). Using the first order approximations \( \sinh Z = \sin Z = Z \) in eqn. 2-1 gives

\[ V = 2q \ln \frac{\pi x}{s}. \quad 2-5 \]

Differentiating with respect to \( r \) yields an expression for the electric field.
\[
E = \frac{V_0}{r \ln \frac{\sinh(\pi L/s)}{\sinh(\pi d/2s)}},
\]

where \( V_0 \) is the applied voltage. This implies that the MWPC potentials are for all practical purposes cylindrical near the wires.

The MWPC has a relatively large electron drift region, where the gas multiplication takes place typically within just a few wire radii from the wire. The equipotentials in the outer drift region are characteristically flat and parallel to the high voltage plane, suggesting an almost constant field in the \( y \) direction. For example, at \( y = s/2 \), \( E_y(0,s/2) \) and \( E_y(s/2,s/2) \) differ by only \( \pm 9\% \). At \( y = 1.25 \, s \) they are equal to one part in \( 10^3 \). Thus, to a very reasonable approximation, the MWPC electric field distribution is one that varies as \( 1/r \) near the wires and is uniform for \( y > s/2 \).

From the above discussion it is clear that each MWPC wire operates as a cylindrical proportional counter. By cylindrical counter is meant the type in which one counting wire is mounted along the axis of a thin-walled metal cylinder to which high voltage is applied. Within the counter the equipotentials are everywhere cylindrical and the electric field is given by
$$E = \frac{V_0}{r \ln \frac{r_2}{r_1}}$$

where $V_0$ is the applied voltage, $r_1$ the radius of the counting wire, $r_2$ the inner radius of the cylinder, and $r_1 < r < r_2$. The equation for the field near the wires of a MWPC (eqn. 2-6) is identical to the above except for a constant depending on similar counter construction parameters. Since multiplication takes place only very near the wires, where indeed $x, y \ll s$, the proportional amplification process about each wire in a MWPC should be identical to that about the central wire in a cylindrical proportional counter.
B. The Proportional Amplification Process

Gas amplification commences when an electron in its last mean free path before reaching the wire gains sufficient energy to ionize. The voltage $V_p$ at which this occurs is called the threshold voltage. Assuming each of $n$ initial electrons formed by an ionizing event multiplies by a factor $A$, the total number of electrons collected on a wire is equal to $nA$.

Let $\alpha$ equal the number of ion pairs formed by an electron in each cm of drift toward a wire. Then

$$\frac{dN}{dx} = \alpha N,$$  \hspace{1cm} (2-8)

where $dN$ is the number of new electrons formed by $N$ electrons in this process in a distance between $x$ and $x + dx$. The quantity $\alpha$ is called the first Townsend coefficient and is a function of the field strength, the composition of the gas, and the pressure of the gas. If $\alpha$ is independent of $x$, integration yields

$$N = N_0 e^{\alpha x},$$  \hspace{1cm} (2-9)

where $N_0$ is the initial number of electrons. An empirical expression due to Townsend is$^{34}$
\[ \alpha = A p \, \text{Exp}(-Bp/E), \]

where \( A, B \) are constants determined by the particular experiment, \( E \) is the field, and \( p \) is the pressure.

Detailed discussions of \( \alpha \) for various gases may be found in treatises on gas discharges. \( ^{35,36,37} \)

The amplification factor (or gas gain) \( A \) is defined as the number of electrons reaching a counting wire per initial electron produced by an ionizing event.

Therefore

\[ A = \text{Exp} \int \alpha \, dx. \]

An expression due to Rose and Korff which defined \( A \) in terms of experimentally measurable quantities is \( ^{38} \)

\[ A = \text{Exp} \left\{ 2(apcr_1 V)^{1/2} \left[ \left( V/V_p \right)^{1/2} - 1 \right] \right\}, \]

where \( p \) is the pressure, \( c \) is the distributive capacity of the counter, \( r_1 \) is the wire radius, \( V \) is the applied voltage, \( V_p \) is the threshold voltage, and \( a \) is the rate of increase of the ionization cross section with energy, which depends on the types of gases used.

\( V_p \) is a function of wire spacing, wire diameter, gap length, gas type(s), and gas pressure. It is the voltage required to create an electric field \( E_p \) at the
wire surface strong enough to cause ionization in the last electron mean free path. Therefore

\[ E_p = \frac{\xi}{l_e} \]

where \( \xi \) is the average electron ionization potential for the gas(es) used. \( V_p \) may thus be obtained from eqn. 2-6 with \( E = E_p \) and \( r = d/2 \). Therefore

\[ V_p = \frac{\xi d}{2l_e} \ln \frac{\sinh(\pi L/s)}{\sinh(\pi d/2s)} \]
C. Factors Governing MWPC Operation

An understanding of the way in which factors such as wire size, wire spacing, gap length, gas composition, and gas pressure affect MWPC operation is very useful in designing counters for particular experiments or for special purposes. For example, most MWPCs are used as position-sensitive detectors, therefore the wire spacing becomes a critical parameter since it determines the spatial resolution of the counter. Counters detecting minimum ionizing particles such as high energy electrons or pions require high overall gas gains, whereas gain would not be so important if lower energy protons, deuterons, etc. were to be detected. Counters used in air usually operate at atmospheric pressure whereas counters used in conjunction with vacuum systems usually operate at reduced pressure. Notwithstanding, the overall ability of a counter to resist breakdown or sparking at or near the required operating voltage often restricts or limits the various counter parameters.

1. Wire Diameter

From eqn. 2-6 the field varies as 1/r near the wires so that as the wire diameter is reduced, the applied voltage may also be reduced while maintaining the same
field at the wire, and thus the same amplification.

Consider two otherwise identical MWPCs with wires of radii \( r_1, r_2 \) operating at voltages \( V_1, V_2 \) respectively. From eqn. 2-6 the field \( E_{1,2} \) at the wire of counters 1 and 2, respectively, is given by

\[
E_{1,2} = \frac{V_{1,2}}{r_{1,2} \ln \frac{\sinh(\pi L/s)}{\sinh(\pi r_{1,2}/s)}}.
\]  

To keep the same field at the surface of the wires implies

\[
\frac{V_2}{V_1} = \frac{r_2}{r_1} \frac{\ln \frac{\sinh(\pi L/s)}{\sinh(\pi r_2/s)}}{\ln \frac{\sinh(\pi L/s)}{\sinh(\pi r_1/s)}}. \tag{2-14}
\]

For example, the above voltage ratio for \( s = .100" \) and \( L = .250" \) in going from \( .002" \) to \( .001" \) diameter wire is only 0.53, which indicates that with the finer wire one may obtain the same pulse sizes with only about half the operating voltage.

There are, however, practical limitations to the size of wire used. Wire \( .001" \) or less in diameter is very fragile and becomes somewhat difficult to tension and to wind. Furthermore, it is difficult to obtain wire
.001" or less in diameter that is homogeneously circular in cross section. Any portion of the wire surface having a radius of curvature smaller than the radius corresponding to circular cross section will create fields much higher than average and will often lead to breakdown before the operating voltage is reached.

2. Wire Spacing

Consider two otherwise identical MWPCs with wire spacings \( s_1 \) and \( s_2 \). Using first order approximations for the \( \coth \) and \( \cot \) functions in eqns. 2-4a,b and equating \( E_1 \) and \( E_2 \) implies \( q_1 = q_2 \), where \( q \) is the total charge per unit length of wire. \( q \) is a function of \( s \) and, as eqn. 2-2 indicates, a smaller wire spacing requires a larger applied voltage to maintain the same charge:

\[
V_2 = \frac{\ln \frac{\sinh(\pi L/s_2)}{\sinh(\pi L/s_1)}}{\ln \frac{\sinh(\pi r_1/s_2)}{\sinh(\pi r_1/s_1)}}
\]

Using the above relation with \( L = .250" \), \( r_1 = .001" \), it is calculated that for \( s = .100", .075", .050", \) and \( .025" \), the voltage ratios (relative to \( V_1 \)) are 1.00, 1.22,
1.67, and 3.09 respectively. Thus, much higher voltages are required for smaller wire spacings and breakdown may occur particularly at regions of higher than average field if one attempts to increase the MWPC spatial resolution by decreasing the wire spacing only.

3. Gap Length

Consider again two otherwise identical MWPCs with gap lengths \( L_1, L_2 \). By treatment similar to that in section 2 (wire spacing), the voltage ratio is

\[
\frac{V_2}{V_1} = \frac{\sinh(\frac{\pi r_1}{s})}{\sinh(\frac{\pi L_2}{s})} \div \frac{\ln \left(\frac{\sinh(\frac{\pi r_1}{s})}{\sinh(\frac{\pi L_2}{s})}\right)}{\ln \left(\frac{\sinh(\frac{\pi r_1}{s})}{\sinh(\frac{\pi L_1}{s})}\right)},
\]

where \( r_1 \) is the wire radius. Using the above relation for \( s = 0.100" \), \( r_1 = 0.001" \), \( L_1 = 0.250" \), and \( L_2 = 0.125" \), the voltage ratio is only 0.63 which implies that one may maintain the same amplification factor \((A)\) with less voltage in a reduced gap counter. But, the total number of electrons collected on a wire is equal to \( nA \), and reducing the gap correspondingly reduces \( n \), since the counter is thinner. If the initial ionization per cm is constant, then \( n \) should vary directly with \( L \).
However, \( A \) is a rapidly increasing exponential function of \( V \) for \( V > V_p \), so that more electrons may be collected with less voltage in a reduced gap counter.

Reducing the gap should be effective in reducing the additional voltage needed for reduced wire spacings. For the counter parameters given in section 2, the voltage ratios were 1.00, 1.22, 1.67, and 3.09. If the gap were reduced from .250" to .125", the above ratios would be only 1.00, 1.15, 1.48, and 2.55 respectively.

4. Gas Pressure

The pressure at which a MWPC operates is often determined by the use of the detector. For example, a large-window MWPC operating in air would run at atmospheric pressure, but a similar MWPC connected directly to or operating within a vacuum system would operate at much reduced pressure due to the large force on the window. Operating at reduced pressure will accordingly reduce \( n \), the number of initial electrons, and thus give a smaller pulse even if \( A \) were the same. For constant specific ionization, \( n \) should vary directly with the pressure \( p \). However, if the pressure is reduced by a given factor, the electron mean free path will increase
approximately by the same factor. This reduces $E_p$ and $V_p$ by the same factor (eqns. 2-13,14). Since $A$ rapidly increases exponentially for $V > V_p$ (eqn. 2-12), acceptable pulse sizes result from reduced pressure operation, whereas the high threshold voltages associated with higher pressures may cause a counter to break down before the necessary operating voltage is reached. It should be recalled that cylindrical proportional counters frequently operate at typically 0.1 atm pressure at the expense of construction complexities and a relatively thick window.

5. Gas Constituents And Quenching

A common gas mixture used in cylindrical proportional counters and some MWPCs consists principally of a counting gas (e.g. A, Ne, Kr, Xe) and a smaller portion of a quench gas, (e.g. methane, butane, propane) usually an organic gas with polyatomic molecules.

The process of quenching has been understood since early experiments with cylindrical proportional counters. The gas amplification for varying voltages, wire radii, gas components, and gas pressures has been measured\textsuperscript{38}) and compared with eqn. 2-12. Agreement was good except when the relative or absolute amount of quench gas
(methane in this case) was reduced too far. This caused the gas amplification to rise more steeply with voltage than predicted by the formula, indicating an additional source of electrons. Many photons originate in an avalanche from excited argon atoms. Ranging in energy from 11.5 to 15.7 eV, these ultraviolet photons would liberate photoelectrons from a metal cathode and the discharge would continue indefinitely. The addition of a polyatomic (four or more atoms) gas which is usually organic will terminate or quench this continuous discharge, the reason being that most of these gases decompose in the ultraviolet and have continuous absorption spectra in the same energy range as the photons emitted by argon, a common counter gas. Diatomic molecules and some light polyatomic ones, on the other hand, have in general stable electronic states with well defined vibrational-rotational structure well above the decomposition level of the molecule. Excitation of the molecule into this energy region results in re-admission of the absorbed photon or fluorescence and only rarely in decomposition. Hence, the photons would not be quenched by a diatomic gas.
Successful MWPC operation has been achieved using pure quench gases such as di-methyl propane and iso-butane. Although they require high threshold voltages, high gains are obtainable due to the large energy loss of ionizing particles in them (table 2-1). Gases with high specific ionizations such as Kr and Xe unfortunately are prohibitively expensive. Gases such as iso-butane and di-methyl propane absorb about twice as much energy as argon and are yet relatively inexpensive. Of course, some gases may be preferred, in view of other physical processes involved such as scattering, absorption, or perhaps destructive chemical reactions between the gas and components of the counter.
<table>
<thead>
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<th>Gas</th>
<th>Energy loss in keV per cm, at STP, of 1.3 MeV electrons</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
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</tr>
<tr>
<td>He</td>
<td>0.32</td>
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<tr>
<td>Ne</td>
<td>1.44</td>
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<tr>
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<td>CH₄</td>
<td>1.5</td>
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<tr>
<td>Iso-C₄H₁₀</td>
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III. CONSTRUCTION DETAILS
A. The Focal Plane MWPC

A cross section and a photograph of the MWPC designed for magnetic spectrograph operation are shown in fig. 3-1 and fig. 3-2. The various counter pieces shown were machined from high quality G-10 fiberglass.

The most important component of the MWPC was the anode/cathode board upon which were mounted the counting wires and one of the two high voltage foils. The layout of the side upon which the wires were wound is shown in fig. 3-2. The .020" wide copper strips shown were photoetched on the G-10 fiberglass by the same technique used in the manufacture of printed circuit boards. It should thus be noted that the gap length L was effectively determined by the thicknesses of commercially available copper-clad G-10 (e.g. 1/8", 1/4", etc.). A precision-grid mylar sheet was used to assure that the black photoetching masking strips were uniformly and accurately spaced.

Counting wires used included .001", .002", and .004" diameter stainless steel (type 304) and .001" gold-plated molybdenum. Wire spacings tested were .050" and .100". The process of winding the wires onto the anode/cathode board is discussed in appendix C. The
Figure 3-1. MWPC cross section

A. 1/8" aluminum foil clamp
B. Mylar entrance foil
C. High voltage foil
D. Counting wire
E. Scintillator material or 1/8" G-10
F. Scintillator clamp
G. Solder reliefs
H. 4-40 threaded rods (with nuts)
J. Extension of anode/cathode board (for connection to flexible wires)

Note: denotes 1/8" diameter Buna-N O-ring.
Figure 3-2. Photograph of assembled MWPC (top) and anode/cathode board (bottom).
wires were soldered to the copper strips with the aid of Zn Cl flux. Cleanliness of the wires was found to be an absolute necessity for reliable counter operation. When soldering, the wires were masked off with a strip of paper, otherwise flux and solder would splatter on and adhere rigidly to the wires. After soldering, the entire board was scrubbed in soap solution to remove the acid (Zn Cl) which, if left, would attack the wires. Also, being a good electrical conductor, the flux would short some of the wires together if not removed.

Provision for the mounting of two metalized high voltage foils or wire planes was made by photoetching the copper strip shown in fig. 3-3 on the back of the anode/cathode board and on the back of the high voltage foil board. Two types of foils were tested -- .0003" aluminum and .00025" silverized mylar. Mylar was found to be superior to aluminum in that it was not so fragile to mechanical and thermal shock, it could be stretched to eliminate wrinkles, and it was also about one-third thinner. Foil mounting was accomplished by first stretching and taping a sheet of mylar to a clean flat surface. Double-sided adhesive mylar (Scotch) tape was then laid around the perimeter of the 1" x 12" counter window and the taped fiberglass board was firmly pressed down on
the mylar sheet. After trimming away excess foil, small wrinkles were removed by heating with a hot-air gun. The above technique was found to be very reliable. The mylar foil could also be mounted by simply stretching it over the window and taping it directly to the counter piece. But, due to the elongated shape of the window, it was often difficult to eliminate wrinkles completely. This type of foil application has been found particularly suited to large MWPCs with circular or square-shaped windows. The copper strip would allow one to wind planes of horizontal and/or vertical wires, which also may be used as the high voltage planes.

Electrical contact between the two foils was made by placing a screw through each copper tab (fig. 3-3) and tightening a nut down on each piece. A 25 meg-ohm current-limiting resistor was connected between the high voltage screw and the high voltage supply. If arcing were to occur within the counter, the resistor would protect the foils and wires from excessive current damage.

For gas flow purposes, the two foils effectively divided the counter into three separate regions, each of which required its own gas input and output. Six gas grooves were machined from the primary gas holes at
Figure 3-3. High voltage board

A. 1" x 12" counter window
B. Copper high voltage strip
C. Copper tab (for connection to high voltage screw)
each end of the counter to the ends of the 1" x 12" counter window. The grooves provided a common gas flow and also prevented pressure gradients between the three regions from occurring. When operated in air at pressures of .1-.2 atm, relatively thick .001" clear mylar was used for the entrance foil due to the .8-.9 atm inward pressure differential. However, when operated in the spectrograph vacuum system, the entrance foil needed to hold only .1-.2 atm outward pressure, so that a much thinner foil could be used.

Vacuum seals for the counter were made with 1/8" diameter Buna-N O-rings. Holes were drilled each inch around the perimeter of the counter for 4-40 threaded rods (figs. 3-1 and 3-2). Excellent vacuum seals were obtained.
B. Adaptation To Spectrograph Vacuum System Operation

The technique by which the MWPC was adapted for spectrograph vacuum system operation is shown schematically in fig. 3-4. The 47" x 6.5" x 0.5" aluminum vacuum plate was designed to fit on the side of and O-ring seal to the spectrograph camera box. The three inch long cylindrical rod braces rigidly supported the 1/2" stainless steel rods which in turn supported the frame upon which the MWPC was mounted. The vacuum feedthroughs (Spectromagnetic Industries) which were mounted on the vacuum plate, created a moveable vacuum seal about the 1/2" rods.

The aluminum frame upon which the MWPC was mounted is shown in fig. 3-5. The brass disc at each end was pinned at the top and bottom so that it could swivel. The center disc hole was threaded to match the threads near the end of the 1/2" rod, so that as the rods were turned, the frame and MWPC moved accordingly. This swivel feature allowed one end of the frame to be moved independently of the other.

Because of space limitations and heat problems, the associated electronics (app. D) had to operate outside the camera box. This presented the problem of feeding hundreds of independent signals out of a vacuum system.
Figure 3-4. Adaptation for spectrograph operation (top view)

A. MWPC mounting frame
B. MWPC
C. 1/2" stainless steel rod
D. Wire feedthrough board
E. Cylindrical rod braces
F. Vacuum feedthroughs
G. Knobs for turning 1/2" rods
H. Vacuum plate

Note: flexible wires not shown here.
**Figure 3-5.** MWPC mounting frame

A. 3/8" aluminum frame

B. 34" x 2" window

C. Brass disc with threaded 1/2" hole

D. Swivel pins

Note: 1/8" holes for mounting MWPC are drilled at 1" intervals around the 34" x 2" window.
in such a way as to be compatible with the plug-in type amplifier card configuration, and yet allow the counter to be moved inside the vacuum system. In order to feed signals through the vacuum plate, wires (.020" copper strips) were photoetched each .100" on one side of a 1/4" G-10 feedthrough board, the rounded edges of which were precision-machined to match the ends of a corresponding slot in the vacuum plate. The feedthrough board (minus wires) is shown schematically in fig. 3-6. A double vacuum seal had to be made — one to the vacuum plate and one completely around the 1/4" feedthrough. The G-10 board shown in fig. 3-7 fitted over the feedthrough and bolted to the vacuum plate. The 1/4" diameter O-ring was thus made to compress on both the feedthrough and the vacuum plate, providing a double seal. No leaks around the feedthrough were ever detected.

The remaining problem was to connect the feedthrough to the extension of the anode/cathode board, which was oriented 90° to it. Wires were photoetched on flexible .004" G-10. These flexible wires were then aligned on top of those on the feedthrough board and on the anode/cathode board extension. They were clamped down with 1" x 16" brass clamps, which were fitted with set screws for making a pressure electrical contact along the entire
Figure 3-6. Wire feedthrough board

Note: Photoetched wires (running lengthwise) not shown here.
Figure 3-7. Double-seal O-ring clamp

A. O-ring groove
B. Mounting holes
C. 1/4" x 11" slot
D. 1/4" diameter O-ring in groove
length of the clamp. The flexible material allowed the counter to be moved across the focal plane without changing the electrical contact. A side view of the feedthrough system is shown schematically in fig. 3-8.

A totally absorbing scintillator-light pipe system (fig. 3-9) was designed to operate behind the focal plane MWPC. A 1/8" sheet of NE 111 (Nuclear Enterprises) scintillator material was glued to a 1/4" lucite sheet with Pilot optical bonding epoxy (Pilot chemicals). The end of the lucite light pipe was pressed to the face of a photomultiplier tube, the optical joint being made with Dow-Corning optical contact fluid.
**Figure 3-8.** Wire feedthrough system (side view)

A. MWPC mounting frame
B. MWPC
C. Flexible wires
D. Wire feedthrough board
E. Vacuum plate
F. Double-seal O-ring clamp
G. Electronics box
Figure 3-9. Backup scintillator-light pipe system

A.  1/8" NE 111 scintillator
B.  1/4" lucite light pipe
C.  Photomultiplier tube
D.  Tube base
IV. EXPERIMENTAL RESULTS

A. Problems Encountered And Remedied

1. Breakdown Phenomena

The original spectrograph MWPC design utilized .001" diameter stainless steel wires at .050" spacing and a .250" gap length. The high voltage planes were .004" stainless steel wires wound orthogonally to the counting wires at .050" spacing. Gases used were argon and iso-pentane in an approximate 1:1 ratio with a total pressure of about 10 cm Hg. This particular design was well suited for focal plane application since the .050" spacing almost equaled the spectrograph spatial resolution and the high voltage wires made the counter thinner than one with say aluminum foils. However, corona and sparking repeatedly occurred below the necessary operating voltage. This instability was found to be definitely related to 1) wire non-uniformity 2) the use of wires for high voltage planes 3) too small a wire spacing and 4) insufficient wire tension. Each of these factors will be briefly discussed along with steps taken to achieve a more stably operating counter.

a. Wire non-uniformity: When examined under a microscope, the .001" wire appeared to be somewhat ribbon-shaped in cross section instead of circular. Moreover,
examination of random samples from a 1000 foot spool showed this to be the norm rather than the exception. As mentioned previously, a non-circular wire cross section leads readily to higher than average field strengths. The counter was rewound with .002" stainless steel wire, which was observed to be relatively circular in cross section. With 2800 V only 20 mV signals could be detected from 8 MeV alpha particles. The total gas pressure as well as the gas types and relative concentrations were varied, but the high voltage instability could not be eliminated. However, the marginal operation seemed to indicate that this type of arrangement might be acceptable if a smaller wire could be found which was uniformly circular in cross section and strong enough to be sufficiently tensioned.

b. High voltage wire planes: The counter design was changed by replacing the high voltage wire planes with .0003" aluminum foils. The encouraging results included reduced instability with respect to sparking, operation at lower applied voltages, and reduction in the relative concentration of quench gas. Now, the field configurations of two otherwise identical MWPCs, one with wires and one with foils, should be the same except near the wires where the fields become much stronger, in contrast to
the relatively constant parallel field lines near a foil. The sparking appeared (visually) to repeatedly occur in specific places in the counter and not, in general, at random places unless the voltage was further increased. For a uniform metal foil there is no preferential place for positives to be collected, but with high voltage wires the positives are funneled into the high field region near a wire. It should be recalled that such quantities as gas mean free paths, specific ionizations, electron and ion mobilities, etc. are all average values, and that there exist finite statistical probabilities for these quantities being somewhat more (or less) than average. Thus, even though average ion mobilities are typically less than average electron mobilities by several orders of magnitude, non-uniformity in shape of a high voltage wire, in conjunction with the already increased field near it, might possibly further increase the local field sufficiently to cause some continuous ionization by a positively-charged gas constituent, with the subsequent acceleration of the electrons by the high fields near the cathode wires. Also, secondary electron emission and subsequent acceleration away from the cathode could
play a role in the instability, as the cathode wires are repeatedly bombarded by the accelerated positives. Due to similar instability problems, other MWPC experimental groups at Rice University have replaced high voltage wire planes with metalized foils.

Identical operation was obtained with .00025" silverized mylar foils. These are preferable to .0003" aluminum because of mechanical strength, ease of foil mounting, and lower density (0.8 mg/cm² as compared to 2.3 mg/cm²). The MWPC with .050" wire spacing and mylar foils gave pulse sizes of only a few tens of millivolts for densely ionizing alpha particles.

c. Wire spacing: Based on dE/dx estimates, the above-mentioned counter configuration would have given pulse sizes too small to be employed in the detection of 10 MeV or so protons, deuterons, etc. Increasing the wire spacing from .050" to .100" by removing every other wire both increased the stability of the counter and gave increased gains even at lower operating voltages. Pulses as large as 100 millivolts were detected from the same alpha source and 5 millivolt signals were seen from a 2 MeV electron source. Other tests with MWPCs have also indicated that, due to similar breakdown phenomena,
.100" is about the lower limit on wire spacing for the conventional configuration \(^{12}\) due to the much increased high voltage requirements (page 2-10).

d. Wire tensioning: Adequate wire tensioning was found to be essential to stable counter operation. Higher than average fields due to insufficient wire tension may occur for two reasons: First, for a wire located exactly midway between the two high voltage planes, the electrostatic force is ideally balanced. But the equilibrium in unstable to small variations in cathode-anode-cathode spacings. Thus an insufficiently tensioned wire would tend to be pulled out of its mid plane and create a stronger than average field. Secondly, spatial limitations within the spectrograph camera box dictated that the MWPC be designed no more than about three inches tall. This limitations created a serious problem when the counter was operated in air. The .8-.9 atm inward pressure differential forced the counter pieces inward from the long dimension of the counter. This process reduced the tension on the wires and caused them to bow out of their plane, particularly in the center section of the counter. This effect could visually be observed as the counter was evacuated. To help alleviate this problem, an aluminum brace was designed as shown in
fig. 4-1. Holes were drilled and tapped along the edge of the anode/cathode board, allowing outward tension to be placed on the board through the tensioning screws. The bowing effect was observed to disappear in the evacuated counter as these screws were tightened. This problem was absent when operating in a vacuum system because the pressure differential was then outward.

Gold-plated molybdenum wire of .001" diameter was found mechanically too weak to be sufficiently tensioned. The molybdenum wires were loose and bowed out of their plane when wound with 15 gram weight tension, yet the wire broke several times while winding with only 19 gram weight tension. By contrast, .002" diameter stainless steel wire was wound with 290 gram weight tension. These were extremely taut and no bowing problems were ever detected.

2. Spectrograph Fringing Fields

The design of the back-up scintillator-light pipe arrangement (fig. 3-9) has been shown to be a successful one. However, the photomultiplier tube would not function due to the excess magnet fringing field. The photomultiplier tube was originally enclosed in a 1/16"
Figure 4-1. Brace for anode/cathode board

A. Aluminum brace
B. Tensioning screws (typical)
C. Anode/cathode board
D. 1" x 12" counter window
mu-metal shield, but this type shield is effective up to only a few gauss. Heavy steel shielding may eventually be needed. A backup scintillator system would be especially useful in rejection of spurious counter events as well as in measuring particle time of flight and in particle identification in certain cases.

3. Electrical Pressure-Contact System

The electrical pressure-contacts between the flexible wires and the anode/cathode board and between the flexible wires and the wire feedthrough board were tested with a simple resistance meter and repeatedly found to show continuity along the entire length of the counter. However, similar tests on the pressure connection between the wire feedthrough board and the electronics box (fig. 3-8) almost consistently showed small random sections of discontinuity. These areas sometimes could be eliminated by adjusting the tensioning set-screws on the electronics box and testing for continuity prior to installing the counter system in the spectrograph. Alternatively, the system could be installed and regions of discontinuity pinpointed by sweeping a scattered beam across the counter while observing the counter position-dependent signal. However, the elimination of this problem by set-screw tensioning was not found to be
To definitely eliminate this problem, an additional 1/4" G-10 board was photoetched. A driver card and 7 amplifier cards (app. D) were mounted in plug-in type connectors on one end of the board. Each contact of the connectors was routed via .020" photoetched copper strips into a parallel array of .100" spaced strips at the other end of the board. This end of the board was epoxied to the wire feedthrough board and jumper wires (106 total) were soldered between the two boards. Electrical continuity for each of the 106 wires was verified with a standard d.c. ohm-meter. Other MWPC experimenters at Rice University have encountered similar frustrating pressure-contact problems and have solved them by comparable methods.

4. Spectrograph Alignment

The 65 cm magnet may be operated in two different modes -- the horizontal (spectrometer) mode and the vertical (spectrograph) mode. In the horizontal mode, with the aid of a quadrupole lens between the scattering target and the magnet entrance slits, a scattered peak will be somewhat elliptical in shape in contrast to a sharp line focus obtained in the vertical mode. In the
scattering of 8 MeV protons from a thick carbon foil, the elastic proton peak at 45° was observed to have a fwhm of almost 3 wires (.300") with the magnet in the horizontal mode. The magnet was rotated to the vertical mode with the expectation of observing a much sharper focus. To the contrary, the scattered peak was diffused over almost four inches. The MWPC was moved up to several inches either side of its original position to ascertain that the counter was not just positioned to one side of the focal plane. No appreciable effect was observed. All but about 1/4" of the MWPC entrance slit was then masked with 1/16" aluminum, and the scattered proton beam was again swept across the counter. The peak was shown by this method also to be about four inches broad. As expected, only about three or four wires fired.

Magnet alignment problems were suspected since it could be visually observed that the entrance axis of the magnet was an inch or so higher than the exit axis from the target scattering chamber. Positioning screws for all three dimensions are located at the base of the magnet, yet alignment in the vertical mode was not attempted, since basic counter operating characteristics could also be obtained with the magnet in the spectrometer mode.
B. Counter Operating Characteristics

In order to be employed as a research instrument in a magnetic spectrograph, the MWPC should possess at least the following two characteristics: 1) uniformly high detection efficiency along the entire counter length and 2) spatial resolution comparable to those obtained with solid state detectors or photographic emulsions.

1. Experimental Design

It was desired to test the extent to which the focal plane MWPC possessed the above two characteristics. 6 MeV protons were scattered from a thin 10 μg/cm² carbon foil and the elastic peak was observed at 45°. Due to previously mentioned magnet alignment problems, the magnet was operated in the horizontal (spectrometer) mode with the quadrupole lens. A position-sensitive solid state detector was used as a reference for both efficiency measurements and line widths.

2. Solid State Detector Measurements

The position-sensitive solid state detector used was manufactured by Nuclear Diodes, Inc. It was 600μ thick and had an active area of 10 mm x 50 mm. It was mounted in the focal plane at the position such that incoming particles were bent 90° by the magnet.
this position the focal plane is oriented approximately 60° to the paths of the focused particles, as indicated in fig. 6-1. The spectrograph moveable detector mount, designed specifically for solid state detectors, is skewed at approximately 60° to the focal plane, so that the solid state detector was perpendicular to the paths of the particles detected. The same particles entered the MWPC at a glancing angle of 60°, since it was aligned along the focal plane.

The solid state detector gives two pulses -- one is proportional to $E$, the energy loss of the particles in the detector, and the other is equal to the quantity $Ex/L$ where $L$ is the length of the detector and $x$ is the position from one end of the detector. The electronics used are shown in fig. 4-2.

A tantalum mask with a 46 mm x 8.3 mm slit was mounted over the detector. Because the thickness of the detector was 600µ, 6 MeV protons were chosen so that the elastically scattered ones (5.71 MeV at 45°) would be completely stopped by the detector. The position spectrum thus obtained is shown in fig. 4-3. A position signal calibration was made by moving the elastic peak from one end of the 46 mm slit to the other. A fwhm of 12 channels, which was equivalent to 0.76 mm, was
Electronics used with position-sensitive solid state detector.
Figure 4-3. Position signal spectrum obtained from solid state detector.
Channel Number

Counts

Channel

\[
\text{FWHM} = 0.76 \text{ mm.}
\]
thereby determined. 21,860 protons were observed in the elastic peak for an integrated beam on target of 400 μcoul.

3. MWPC Measurements

a. Line shapes: The solid state detector was removed and the MWPC was mounted in the focal plane. Spectra were taken at the same magnet setting for different operating voltages. Also the various bits (10 volt logic signals) generated by the MWPC electronics were scaled: 1) Bit 1's -- A bit 1 is generated whenever a half-wire position is determined. Thus, a bit 1 is generated only if an even number of adjacent wires fire simultaneously. 2) Bit 11's -- A bit 11 is generated whenever 3 or more adjacent wires fire simultaneously. 3) Bit 12's -- A bit 12 is generated whenever 4 or more adjacent wires fire simultaneously. 4) Bit 10's-- A bit 10 is generated whenever non-adjacent wires (or groups of wires) fire simultaneously. 5) Total triggers-- A trigger pulse is generated whenever a 702C amplifier detects a MWPC pulse that is larger than the given discrimination voltage level. Additional electronics used with the MWPC are shown in fig. 4-4.

The spectra obtained for the different operating voltages are shown in fig. 4-5. Each increment in
Figure 4-4. Additional electronics used with MWPC

Note: Linear gate and stretcher is used to eliminate the sharp spikes on the output pulses of the analog output module.
Figure 4-5. MWPC spectra for constant magnetic field and varying operating voltages

Note: The increment in the abcissa corresponds to a half-wire position.
a) 2700 Volts
fwhm = 10.2 mm

b) 2750 Volts
fwhm = 8.9 mm
c) 2800 Volts
fwhm = 7.6 mm

d) 2850 Volts
fwhm = 6.4 mm

e) 2900 Volts
fwhm = 4.4 mm
f) 2950 Volts
$\text{fwhm} = 3.8 \text{ mm}$

g) 3000 Volts
$\text{fwhm} = 3.8 \text{ mm}$

h) 3050 Volts
$\text{fwhm} = 3.2 \text{ mm}$
abcissa corresponds to a half-wire position. The relatively low efficiencies of half-wire events, as well as total events, are clearly evident in fig. 4-5 a,b. The number of the various bits scaled for each spectrum, relative to the total number of triggers, is given in table 4-1. This data is plotted against the applied counter voltage in fig. 4-6.

The MWPC electronics were designed so that the position signal, for two or more adjacent wires firing simultaneously, is the same as if one wire were to fire at the geometric centroid of the group. Fig. 4-6 shows that in the voltage region where the peak widths were the narrowest, almost all of the events fell into the bit 12 category — i.e. four or more adjacent wires fired simultaneously. By subtracting the number of bit 12's from the number of bit 11's, it was determined that events such that exactly three adjacent wires fired simultaneously were essentially non-existent in the voltage region where the peak widths were the narrowest.

The multiple firings can be understood from the geometry of the MWPC on the focal plane. For a gap length of .250" and a glancing angle of 60°, the path length of a particle in the active region between the two high voltage foils is 1". When this path is
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<tr>
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<td>45.3</td>
<td>94.8</td>
<td>93.5</td>
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<tr>
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<td>45.7</td>
<td>95.4</td>
<td>95.2</td>
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<tr>
<td>3050</td>
<td>46.5</td>
<td>95.8</td>
<td>95.1</td>
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Figure 4-6. Relative number of multiple-event bits generated by the MWPC electronics.

a) Bit 1's
b) Bit 11's
c) Bit 12's
projected on the axis of the high voltage foils, it may be observed that ionization is spread over an area containing almost 9 wires (for .100" spacing.) If the scattered proton group were about 1 mm wide, then ionization would be spread over an area containing almost 10 wires.

Spectra were taken for the same 400 μcoul target current exposure at random places in the counter by varying the magnetic field. Several of these spectra are plotted in fig. 4-7. Also included in fig. 4-8 are several spectra taken at random positions along the counter with a thick 2.3 mg/cm$^2$ aluminum foil in place of the carbon foil. Integrated target currents for these spectra were 150 μcoul.

The best fwhm of 3.2 mm (for the spectra shown in fig. 4-5) was somewhat greater than the 0.76 mm width obtained with the solid state detector. However, when multiple scattering of the entrance foil and the first high voltage foil are taken into account, along with the fact that the 0.76 mm width was obtained with the solid state detector perpendicular to the paths of the incident particles, the fwhm of 3.2 is quite reasonable. The rms multiple scattering angle was calculated for both a .001" and a .00025" mylar foil. The angles thus
Figure 4-7. MWPC spectra taken at random positions along the counter

Counter voltage = 2950 Volts
Figure 4-8. MWPC spectra taken at random positions along the counter.

Target = $3.2 \text{ mg/cm}^2$ aluminum.
obtained, approximating the mylar foils with carbon foils, were 0.015 rad and 0.009 rad respectively. It was thus calculated that multiple scattering in the MWPC foils would broaden a 0.76 mm wide peak to almost 3.5 mm, when projected onto the plane of the wires.

b. Efficiency measurements: Consider a given number of monoenergetic particles incident upon a MWPC. Since the gas amplification is a statistical process, the energy a particle loses in traversing the counter will be a gaussian distribution. Therefore, the signals directly off a given wire will have an average size $\bar{E}$ and some standard deviation $\sigma_E$. If, for example, the threshold voltage for the 702C amplifiers were set at exactly $\bar{E}$ millivolts, then only one-half of the events would fall above the threshold and be accepted. If the voltage, and thus the gas amplification, were increased such that the new $\bar{E}$ were greater than the threshold voltage by several $\sigma_E$, then efficiencies approaching 100% could be expected. If each wire is to count with the same efficiency, then each wire must have the same amplification factor and each 702C amplifier must discriminate at
exactly the same voltage. Increasing the gas amplification such that 99+\% of the signals resulting from the ionizing events are accepted, also increases the probability that a background count will fall above the discrimination level.

The same tantalum slit that covered the solid state detector was placed over the MWPC entrance slit. The total number of signals recorded in the elastic peak region is given in table 4-2, and plotted in fig. 4-9. The solid state detector counted 21,860 protons in the elastic peak for the same integrated target current exposure. Table 4-3 shows the total number of events detected in the elastic peak region at random positions along the MWPC. The shapes of these peaks are plotted in fig. 4-7.

It was observed that for \( V \geq 2800 \text{ Volts} \), the number of events recorded by the MWPC is a few percent greater than the number detected by the solid state detector. There is also a slight increase with voltage in the total number detected. However, the number counted in background spectra, taken without any beam on target, was small when compared to the differences in table 4-2 between the two counters. This seems to imply that most of the MWPC random events occurred when the counter was
<table>
<thead>
<tr>
<th>Voltage</th>
<th>Total number of events recorded in elastic peak</th>
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<tbody>
<tr>
<td>2700</td>
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<td>2750</td>
<td>18,140</td>
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<td>3000</td>
<td>23,135</td>
</tr>
<tr>
<td>3050</td>
<td>24,292</td>
</tr>
</tbody>
</table>

*Total number of events recorded with solid state detector* 21,860
Figure 4-9.

Total number of events falling in elastic peak region vs voltage for a 400 μcoul beam exposure.
Table 4-3

Total number of events recorded in elastic peak at random positions along the MWPC:

23,741
23,529
22,030
22,698

Total number of events recorded in elastic peak by solid state detector:

21,860
actually counting. Such beam-dependent background events
could include neutrons, X-rays, or recoil protons.

A rough estimate of this background can be made
from table 4-1. The total triggers scaled included
both elastic proton counts and background counts.
Because of the high proton angle of incidence, all
elastic proton events should be multiple events
(bit 12's). However, there is no a priori reason for
background events to preferentially fall into this
category. Therefore, it may be reasonably estimated
that 95% of the total events were due to elastic protons
and only 5% were due to background.

This is further shown by comparing the total
number of events falling in the proton peak region with
the number of events recorded in the total 1024 channels.
This was done for the data shown in fig. 4-5 f,g,h.
The number of events recorded in the 1024 channels was,
as expected, equal to the number of trigger events.
The number of events under the proton peak was consis-
tently 94% of the total number of events, indicating a
background of about 6%.

Corrections should also be made for dead time of
the electronics system which, when analyzing only one
wire plane, is 54 microseconds. Since the data
accumulation rate was only about 50 counts/second, this would yield a dead time correction of only 0.27%, which is small compared to the 6% background.

If the data in tables 4-2 and 4-3 is adjusted by a factor of 0.94, then it is found that at most the number of thereby determined elastic proton events statistically differs from the number recorded by the solid state detector by only 2%. Thus, a lower limit of 98% could be conservatively placed on the MWPC efficiency. The above discussion emphasizes the need for a back-up scintillator system to eliminate background events. Precise efficiency measurements could be made only by this or a comparable method.
V. REMARKS AND CONCLUSIONS

The spirit of this project was centered around the concept of obtaining a working MWPC system in the magnetic spectrograph. Indeed, the complete adaptation to the magnet vacuum system was a non-trivial problem. Given a working system, one may then more easily modify the MWPC to achieve desired operating characteristics.

The necessity of increasing the wire spacing to .100" imposed somewhat of a limitation upon the spatial resolution capabilities of the counter. Reduced wire spacing operation may indeed be possible by modifying the counter in some of the following ways: 1) Use of a uniformly circular wire of less than .002" in diameter 2) Use of a smaller gap length 3) Use of intermediate high voltage wires or intermediate high voltage grids.

The high angle of incidence of the focal plane to the incoming particles also imposes limitations upon the spatial resolution capabilities of the MWPC. Increased spatial resolution may be obtained by modifying the counter in some of the following ways: 1) Use of a thinner entrance foil 2) Use of a thinner high voltage foil 3) Reduction in the gap length between the wires
and the high voltage foils. 4) Reduction in the gap between the entrance foil and the high voltage foil.

A back-up scintillator system would greatly enhance the utility of the MWPC for focal plane detection. It would facilitate absolute efficiency measurements, particle time of flight measurements, and particle identification in certain cases.
VI. APPENDICES

A. Magnetic Spectrograph — Physical Layout And Focusing Properties

The system utilized in the present work is a 65 cm broad range magnetic spectrograph manufactured by Spectromagnetic Industries. The ion beam is supplied by the Rice University Tandem Van de Graaff accelerator. The spectrograph system possess essentially three physical components: a target chamber, the magnet pole pieces, and a camera box.

The target chamber, in addition to housing targets, provides for the housing of a moveable solid state detector and a moveable quartz to monitor the target current. A moveable vacuum seal allows the spectrograph to be rotated with the chamber under vacuum.

The pole pieces are by far the most critical components of the spectrograph. The spectrograph is guaranteed to have a field uniformity of one part in 2000 for fields up to 12,500 gauss, exclusive of the pole piece perimeter which is affected by the fringing field. Each 13,000 pound pole piece is made from high quality D. C. magnetic ingot iron. The coils are wound with hollow-core copper conductor which is water-cooled for
high thermal efficiency. At the entrance to the pole pieces are both horizontal and vertical slits which limit the angular acceptance of the spectrograph. Provision is also made between the two pole pieces for the insertion of a nuclear magnetic resonance probe by which the field strength can be determined very accurately.

The camera box is a somewhat triangular-shaped enclosure inside of which are moveable mounts for both photographic emulsions and solid state detectors. The vacuum plate directly behind the focal plane position is removeable and it seals to the camera box frame with an O-ring. A hard vacuum is maintained within the entire system by diffusion pumps at the target chamber and the camera box. A hand-operated hydraulic pump allows the entire spectrograph to be rotated in the horizontal plane, thereby giving angular observations ranging from $-10^\circ$ to $+150^\circ$. Rotation of the magnet in the vertical plane is also possible. This allows the system to operate in either the vertical or horizontal mode.

The geometric features relating to the focusing properties of a spectrograph are shown in fig. 6-1. The important requirement here is that the source of particles be located a distance $R_0$ from the boundary of a uniform magnetic field, the entrance and exit edges of which also
Figure 6-1. Geometric features of a magnetic spectrograph

A. Source (position of scattering target)
B. Circular field limit
C. Approximate shape of pole pieces
D. Focal Plane
F. Adjustable entrance slits

Note: $E_0$ refers to the energy of particles bent 90° by the magnet.
have a radius of curvature equal to $R_o$. For particles with a radius of curvature $R_o$, the source and image are symmetrically located as shown and second order focusing is obtained. With this geometry the central trajectory of any other particle having a radius of curvature $r$ ($r \neq R_o$) also leaves the field normal to the field boundary. From equations of ion optics it can be shown that the focal points for particles of radius of curvature $r$ lie along a hyperbola, the parametric equations of which are

$$ X = \frac{2R_o(r^2 - R_o^2)}{3R_o^2 - r^2}, \quad Y = \frac{4rR_o^2}{3R_o^2 - r^2} \tag{6-1} $$

where $X$ and $Y$ are as shown in fig. 6-1. Due to the fringing effects the magnetic field does not stop at the actual pole boundaries. The most important of these effects causes the field to have a radius larger than that of the poles by approximately the pole gap. $R_o$ is therefore effectively 68.2 cm.
B. Continuous Gas Flow System

The continuous flow, pressure regulated system which supplies gas to the MWPC is illustrated in fig. 6-2. The gas bottles are fitted with diaphragm-type pressure regulators which are set at just above atmospheric pressure. This assures a constant pressure at the input of each Matheson 150 mm flowmeter unit. The flowmeters allow the gases to be mixed in any desired proportion and allow an accurate reading of the total gas flow through the counter. The Matheson vacuum regulator (model 49) is designed to maintain a definite vacuum within the range of 2-655 mm Hg and to allow the proper amount of gas to be bled into the system under constant evacuation to maintain the set vacuum. The 760 mm mercury manometer gives an accurate reading of the pressure within the counter system. Output throttle valve "H" regulates the total gas flow rate through the system. Bypass valve "J" connects the MWPC directly to the spectrograph camera box vacuum system, thereby providing for equal pressures in each when the camera box vacuum is changed. Since the camera box is equipped with a diffusion pump, the bypass valve allows the MWPC and all parts of the gas flow system to be pumped down to a hard vacuum before any gas is admitted to the system. Although
Figure 6-2. Regulated gas flow system

A. MWPC
B. MWPC mounting frame
C. From regulated gas bottles
D. Flowmeters
E. Pressure regulator
F. Mercury manometer
G. To forepump
H. Throttle valve
J. Bypass valve to spectrograph camera box (hard vacuum)
provision for two gases is shown in fig. 6-2, typically argon and a quench gas, the system is easily adaptable for use with only one or, in principle, several different gases.
C. Wire Winding System

The ingenious device used to wind the wires onto the anode/cathode board employs a lathe-driven dynamic pneumatic tensioning piston-cylinder arrangement, shown schematically in fig. 6-3. As the lathe gears are engaged, a flat mandrell upon which the anode/cathode board is mounted turns at approximately 15 rpm and the wire is fed from its spool which is connected to a small variable-speed electric motor. The wire then runs around a pulley connected to the top of a lightweight teflon cork located in a glass tube and then through a pulley system on a lathe-geared moveable arm. Two additional pulleys at the top of the glass tube guide the wire in and out of the tube. A partial vacuum is maintained in the lower part of the tube, and thus on the teflon cork which keeps the wire at a constant tension during the winding process. As the mandrell revolves, the amount of wire pulled through the pulley system on the moveable arm varies sinusoidally while the wire spool feed rate is fixed. Thus during each mandrell revolution the teflon cork oscillates a few inches, compensating for the variable winding rate while maintaining constant tension on the wire. The moveable arm, which spaces the wire on the anode/cathode board, is geared to move, to the right or left, exactly "x"
Figure 6-3. Wire winding system

A. Lathe
B. Mandrell
C. MWPC anode/cathode board
D. Wire spool
E. Moveable arm with pulley system
F. Glass tube
G. Teflon cork
H. Pulley system
J. To forepump
K. Counting wire
inches per revolution, where "x" (the wire spacing) is
determined by the various lathe gear ratios available.
The suction in the glass tube, provided by a vacuum
pump, may be adjusted with a simple throttle valve, and the
vacuum may be monitored by observing the water column
height pulled in a clear plastic tube.
D. Associated Electronics

A complete treatment of the Rice University MWPC electronics system is given elsewhere. However, a brief discussion of those parts used with the focal plane MWPC will be given here.

Seven amplifier cards (fig. 6-4) and one driver and power distribution card are mounted on a G-10 board which is epoxied to the wire feedthrough board. Each amplifier card contains 16 identical amplifier circuits. The first stage uses a 702C operational amplifier, and the second employs an integrated circuit comparator (710C). The base line discrimination level is adjusted for all amplifiers simultaneously by varying the reference voltage. One volt on the reference bus gives a discrimination level of one millivolt at the input. The output of the discriminator is a three volt logic signal, thus the overall gain of the two stages can be as high as 3000.

The readout control logic uses a 4 MHz shift clock and a 112 shift register string to determine which of the 112 wires counted. Also, if two adjacent wires are on, the result is a position signal halfway between them. Three on will indicate the position of the middle wire, etc. Other tags are also generated -- indicating more than three adjacent on wires, and another indicating that
Figure 6-4. Photograph of amplifier card (contains 16 amplifiers)
other groups of wires are on.

The output of the readout control logic is next fed into the analog output module. It is an off-line, self-contained system which allows one to visually monitor the position spectra from one or more MWPCs on a display scope. Its output, after being properly shaped, is used as the input to the ADCs which are interfaced to the Rice University IBM 1800 computer.
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