$D + W$ PRODUCTION.

PROPOSAL FOR AN EXPERIMENT TO DETECT THE W MESON AND MEASURE ITS MASS

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(Presented by O. PICCIONI)

While the results of the CERN neutrino experiment are not such as to prove the existence of the W beyond any conceivable doubt, they nonetheless assess a high probability that a W meson exists and that it has a mass approximately in the range between 1.2 and 1.8 GeV.

It, thus, seems highly advisable to do an experiment to seek additional evidence for the existence of the W and indeed to determine its mass value within an error of a few MeV. We are in the process of preparing an experiment on the production of the W from the reaction $P + P \to D + W$. We have arrived at an approximate computation for the cross section, based on the proportionality between cross sections and coupling constants in the comparison between the reactions

$$P + P \to D + \text{pions}; \qquad (1)$$

$$P + P \to D + W. \qquad (2)$$

The coupling constant for pion production is to be taken equal to 1 * for this comparison.

The coupling constant for W production is $(\pi/2)^{-1}\, 10^{-5}\, M^{-2}\, M_w^2$, that is $2.2 \times 10^{-6}\, M^{-2} M_w^2$ where M is the mass of the proton, M_w that of the W.

The crucial point is to understand how the numerous reactions included in (1) such as $D + \pi^+$; $D + \pi^+ + \pi^0$; $D + \pi^+ + \pi^- + \pi^+$ etc. should be taken into account in the comparison with W production.

Obviously, one cannot compare $D + \pi^+$ with $D + W^+$ because of the too great difference in masses. Nor can one, for example, compare $D + \varrho^+$ with $D + W^+$ (apart from the difficulty of determining quantitatively the broad ϱ peak) because the ϱ production is not the only state allowed to pion production. Other states compete with ϱ without correspondingly increasing the total pion production. In fact, the pion production cross section, with final states of unbound nucleons, appears to reach a geometrical limit, when the energy, and therefore the number of channels, increases.

In other words, using a description often used in meson production, first the colliding nucleons produce a mesonic «fireball», then the fireball divides itself into states of one or more mesons in proportion to their statistical weights. We think it reasonable to assume that the pion coupling $g_\pi = 1$ produces the fireball, regardless of the number of possible final states for the decay of the ball.

We draw then the conclusion that $\sigma_\pi = \sigma\,(P + P \to \text{pions in any state} + \text{two nucleons, bound or unbound})$ and $\sigma_w = (P + P \to W + 2 \text{ nucleons, bound or unbound})$ are in the ratio $\sigma_w/\sigma_\pi = 2.2 \times 10^{-6}\, M_w^2/M^2$ providing the value of M_w is comparable to the mass of the «fireball».

When we turn our attention to deuteron production, however, we remark that the fireball produced in $P - P$ collisions must have the charge $+1$ in order to be compatible with deuteron production. Looking at all possible final states, (incoming momentum equal to 2.9 GeV/c) we see that such compatibility obtains only in $\frac{4.4}{28} = 16\%$ of the cases. By contrast, the W^+ can, of course, only be produced with the charge $+1$ so that, in proportion, more W's than pions are produced with deuterons.

Then we look at the reactions $D + \pi^+ + \pi^0$ and $D + \pi^+ + \pi^+ + \pi^-$ at 2.9 GeV/c (not enough data are available at higher momentum). For various reasons we would choose this energy to investigate W production for a W mass of 0.75 GeV. The data of B. Sechi Zorn * give the probabilities for different mass values

*Professor C. N. Yang, private communications. We are most grateful to Professor Yang for his generous and kind cooperation.

* Phys. Rev. Lett., 8, 282 (1962).

of the pions. We observe that the mass of o. 75 GeV is certainly not discriminated against, so that if the coupling constants were the same, it would be at least as probable to produce the W as it is to produce groups of pions of any equivalent mass between .28 and .850 GeV. Since the total cross section given by Sechi Zorn is .2mb, then, taking into account the «advantage» of the W for having always its charge equal to $+1$, we have

$$\sigma(D+W) = 2\cdot 10^{-28}\cdot 2.2\cdot 10^{-6}(75)^2 \times \times \frac{1}{16} = 1.53\cdot 10^{-33} \text{ cm}^2.$$

This value is about ten times larger than the value given by Bernstein *, yet this does not necessarily imply it is wrong. True, our simple approach cannot take into account the «details» of the weak interaction, such as how the various spins and angular momenta are coupled to each other, but it is not probable that this makes our result wrong by an order of magnitude. On the other hand, a computation which follows a succession of Feynman diagrams, selected for their mathematical simplicity, can easily be wrong by more than an order of magnitude.

Finally, we must remember that our computation is for a mass of .75 GeV, while data from CERN point to a value between 1.2 and 1.8.

If we consider the results of Bernstein at least as indicative, the cross section does not change much from one mass value to another one, choosing, of course the proper incident proton energy for each mass. This is reasonable, if we recall that the matrix element is proportional to the square of the mass of the heavy boson.

For heavy values of the boson mass, one may also have reservations because the nucleonic form factor could have a detrimental effect. While, of course, nothing is known for sure about this point, we want to remark that the abundance of antiprotons produced at Brookhaven and Geneva tends to show that heavy masses can indeed be produced by strong interactions, without unexpected difficulties. We have no reason to think that the nucleonic structure for weak and strong interactions is different, and, consequently, we do not expect a drastic loss in W production because of the form factor.

For the branching ratio pertaining to the decay into a muon and a neutrino, we take $\frac{1}{4}$.

* Phys. Rev., **129**, 2323 (1963).

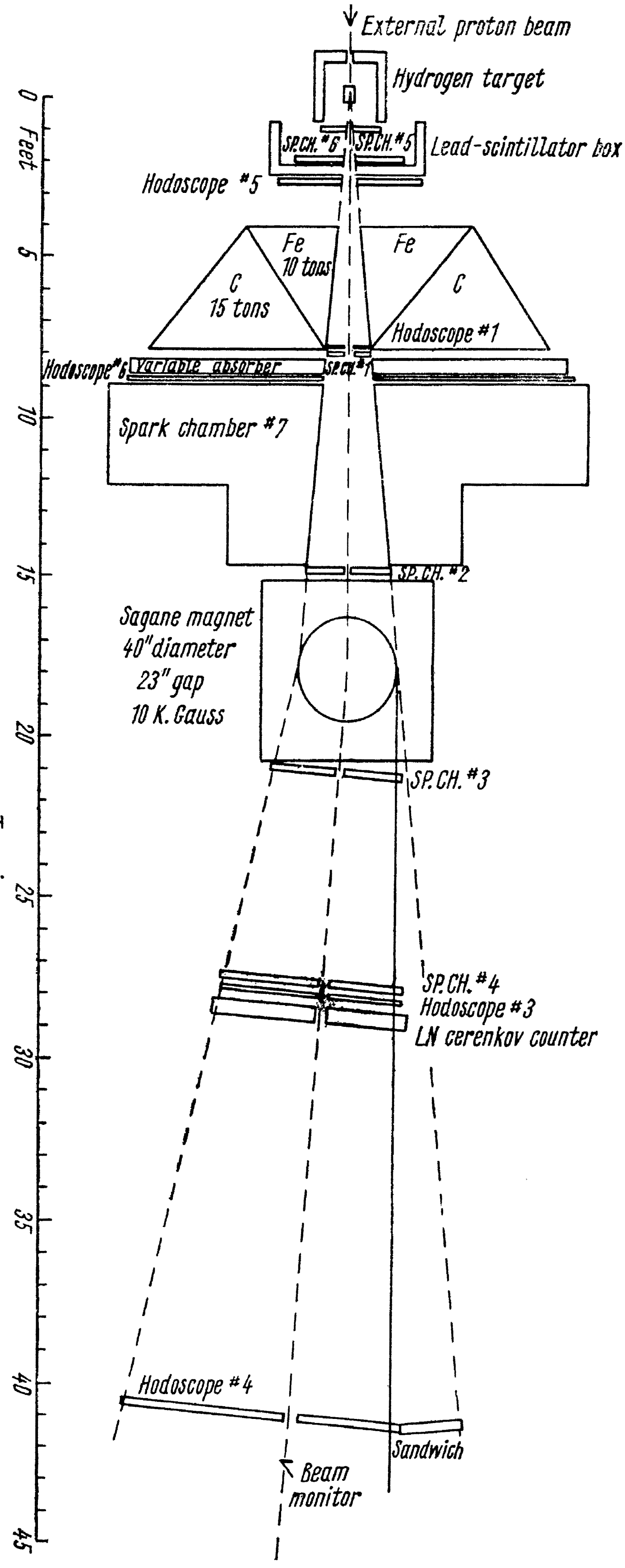
DESCRIPTION OF THE APPARATUS

The apparatus is designed to detect the reaction $P+P\rightarrow D+W$, with the subsequent decay $W\rightarrow\mu+\nu$, in the following fashion: 1) Deuterons produced within a cone of 5 degrees in the forward direction (the so-called deuteron cone) are identified and their momenta and production angles are measured. These measurements determine the mass as well as the angle and momentum of the unseen W meson; moreover, for the two-body decay mode $W\rightarrow\mu+\nu$, kinematics determine uniquely the range of the decay muons at any given laboratory angle. 2) Angle and range of the decay muons are measured within a wide cone of 45 degrees in the forward direction, the so-called muon cone. The consistency of measurement 1) with the results of measurement 2) constitutes an essential criterion for the recognition of true $D+W$ events. Let us now turn to a description of the apparatus, referring in particular of figure.

Incoming from the top is an external «pencil beam» derived from the external beam of the Bevatron. This pencil beam has an angular aperture of the order of a few milliradians, an energy spread of one or two MeV., and a cross section less than 1 sq. in. The intensity of the beam is around 10^9 protons per second, over as long a spill as possible. The pencil beam strikes a liquid hydrogen target some six inches long and two inches wide and proceeds through holes in spark chambers and counters until it essentually leaves the appara tus while still having a cross section of no more than a few square inches.

The deuteron cone performs a momentum analysis by establishing particle trajectories upstream and downstream with respect to a large aperture bending magnet. Hodoscopes 2 and 3 determine the particle positions with sufficient accuracy to make a rough electronic momentum analysis, accurate enough to eliminate the unwanted final states pp and $D\pi^+$. A 6-inch liquid nitrogen Cerenkov counter and a system of time of flight counters serve to identify the deuterons, while giving a rejection factor 10^4:1 for protons and mesons. Finally, if all logical requirements are satisfied, and the spark chambers are triggered, spark chambers 1 through 4 allow a momentum determination of the deuterons to 1% accuracy, which corresponds to about 10 MeV error in the mass of the W.

The apparatus in the muon cone serves the function of establishing particle trajectories



and of identifying muons in fairly close analogy to the deuteron cone. Hodoscopes 5 and 6 are designed to electronically determine whether a particle has travelled in a straight line from the hydrogen target. Moreover, at least three interaction lengths of absorber are placed between these hodoscopes. This arrangement rejects strongly interacting particles by a factor in the order of 10, while muons pass unrejected. Again, when all other logical requirements are satisfied, and the spark chambers are triggered, chambers 5 and 6 provide a measurement of the decay angle of the muon (in the laboratory) to about 0.5 degree accuracy; chamber 7 measures the range of the muons to 3% accuracy, this figure being equal to the range straggling.

Chamber 7, mostly because of its mere size and weight, presents one of the major engineering problems of the experiment.

The most important source of background in the experiment consists of the final state $D\pi^+\pi^0$. As it turns out, the system $\pi^+\pi^0$ may have a mass equal to any presumed W mass; thus the deuteron cone may let the corresponding deuteron pass, while the π^+, if it makes its way through the absorber without interacting, has a momentum and angle equal (within the measuring accuracy) to those of a muon from W decay. Thus, the rejection of the final state $D\pi^+\pi^0$ rests heavily upon the recognition of the presence of a π^0. This is achieved by surrounding the hydrogen target with a box of lead-scintillator sandwiches. We have arrived at a design which should eliminate the final state $D\pi^+\pi^0$ to a sufficient extent.

Of course, the sandwich box is sensitive to neutral pions and gamma rays from any final state, thus being a substantial help in rejecting unwanted background events. Moreover, its peculiar feature of surrounding the hydrogen target completely (except for an entrance hole for the proton beam and an exit hole of the size of the deuteron cone) lends itself to another application; namely, to guarantee that a two prong event was produced in the target. This is achieved by requiring electronically that one and only one particle pass hodoscope 1 of the deuteron cone; that one and only one particle pass the muon cone part of the sandwich box; and that no particle pass the remaining part of the sandwich box. In order to achieve this purpose, as well as in order to alleviate dead time problems in the counters, the sandwich box is subdivided in 80 counters.

The Table gives the rate of several expected types of events.

Estimated event rate and rejection factors

Final State	σ, mb	Events per Pulse	Pb-Sc Sandwich Box	D Čerenkov	Time of Flight	D Cone	μ Cone	D Hodoscope	μ Hodoscope	Triggers per Pulse	Interactions	μ Range	Mass Resolution	Rate per Pulse	Final State
pp	10	$.5\ 10^{7}$	1	10^{-2}	10^{-2}	.7	.01	.01	.1	$3\ 10^{-3}$	.1	.01	---	---	pp
$pn\pi^{+}$	8	$.4\ 10^{7}$	.5	10^{-2}	10^{-2}	.05	.60	.3	.1	.2	.1	.01	.03	$6\ 10^{-6}$	$pn\pi^{+}$
ppn^{0}	4	$.2\ 10^{7}$	10^{-3}	10^{-2}	10^{-2}	.05	.60	.3	.1	$2\ 10^{-4}$	.1	.01	.03	$6\ 10^{-9}$	$pp\pi^{\circ}$
$nn\pi^{+}\pi^{+}$	2	$.1\ 10^{7}$	.3	10^{-2}	10^{-2}	.05	.60	.3	.1	$3\ 10^{-2}$	.1	.03	.03	$3\ 10^{-6}$	$nn\pi^{+}\pi^{+}$
$pn\pi^{+}\pi^{0}$	6	$.3\ 10^{7}$	10^{-3}	10^{-2}	10^{-2}	.05	.60	.3	.1	$3\ 10^{-4}$	.1	.03	.03	$3\ 10^{-8}$	$pn\pi^{+}\pi^{\circ}$
$pp\pi^{+}\pi^{-}$	12	$.6\ 10^{7}$	10^{-4}	10^{-2}	10^{-2}	.10	.90	.3	.1	$2\ 10^{-4}$	.1	.03	.03	$2\ 10^{-8}$	$pn\pi^{+}\pi^{-}$
$D\pi^{+}$	.05	$2.5\ 10^{4}$	1	.8	1	.05	.01	.01	.1	$1\ 10^{-2}$	.1	.01	---	---	$D\pi^{+}$
$DK^{+}\overline{K}^{0}$	.002	10^{3}	.3	.8	1	.10	.80	.3	.1	.6	.1	.01	.03	$2\ 10^{-4}$	$DK^{+}\overline{K}^{\circ}$
$D\pi^{+}\pi^{0}$	.1	$5\ 10^{4}$	10^{-3}	.8	1	.10	.80	.3	.1	.1	.1	1	.03	$3\ 10^{-4}$	$D\pi^{+}\pi^{\circ}$
DW	10^{-7} (1)	$5\ 10^{-2}$	1	.8	1	.10	.80	1	1	$3\ 10^{-3}$	1	1	1	$30\ 10^{-4}$ (2/hr)	DW

Electronic Rejection Factors (Pb-Sc Sandwich Box through μ Hodoscope); Spark Chamber Rejection Factors (Interactions through Mass Resolution)

The W-boson mass range of $1.2\ \text{GeV} < M_W < 1.8\ \text{GeV}$ may be split into four parts of o.15 GeV each as follows:

P_p, CeV/c	T_p, CeV	P_D, GeV/c	M_W, GeV
4.55	3.71	1.87—2.55	1.20—1.35
5.10	4.25	2.00—2.75	1.35—1.50
5.65	4.79	2.10—2.90	1.50—1.65
6.30	5.43	2.20—2.90	1.65—1.80

(1) This value contains a factor $\frac{1}{4}$ for the branching ratio into muon and neutrino. Another factor $\frac{1}{4}$ respect to page 32 is applied as a margin of safety.

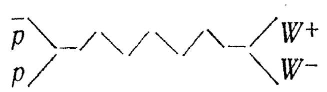
DISCUSSION

A. Zichichi

In connection with the problem of observing the production of intermediate bosons, I would like to mention that we have been studying at CERN two schemes:

$$1)\ \bar{p}+p \to W^{+}+W^{-}, \quad W^{-} \to e^{-}+\nu_{e}, \quad W^{+} \to \mu^{+}+\nu_{\mu} \quad \Big\} \to \mu^{\pm},\ e^{\mp}.$$

This process is described by the following Feynman diagram



Notice that this process is proportional to α^2 where α is the electromagnetic coupling constant.

2) The second proposal studied would use the internal target of the proton synchrotron with 10^{12} protons per pulse incident onto the target. The process would be $p + \left(\frac{p}{n}\right) \to W^{\pm} +$ anything. We would observe the μ's from W-decays. By measuring the angular and momentum distribution at large angles of K and π's, we can predict the corresponding μ-spectrum. We then see if the μ's found at large angles agree with or exceed the expected number. A supplementary check can be made by measuring the polarization of these μ's. The polarization indicates the origin of these μ's. Notice that the cross section for this process goes with $\sqrt{g}$, where g is the β-decay coupling constant.

B. Pontecorvo

I would like to use the fact that you are all tired in order to make a remark of linguistic rather than sicentific character. All the speakers used as notations for neutral leptons the letters ν_e and ν_μ. This seems to be a very convenient notation. On the other hand, the terms which are usually used for neutral leptons-electron and muon neutrinos (and even «electron and muon type of neutrino!»), are too cumbersome. True, sometimes for ν_e the word «neutrino» is used and for ν_μ, the word «neutretto». The last term, however, is not very satisfactory since the last thirty years lost of particle including strong interacting particles had been called that way. In addition, it seems to me that both types of neutral leptons should conserve in their «name» the root «neutrino», which is widely associated with the unique properties of these particles: fantastic penetrating power and the extremely small value of their mass. These properties, I remind you, are already well known outside scientific circles.

Consequently, I propose the following names:

1. Elneutrino, for ν_e;
2. Muneutrino, for ν_μ.

This allows to conserve the general term «neutrino» for both particles.

Concerning the question of Zeldovich how we should call the corresponding antiparticles the answer is:

Notation: $\tilde{\nu}_e$ and $\tilde{\nu}_\mu$

In words: antielneutrino and antimuneutrino.

D. Meyer

The rate of the reaction $\bar{p} + n \rightarrow W^-$ has been calculated by R. R. Lewis. Using values of g_a and g_v of a size given by β-decay a cross section can be calculated. Since the W^- width will be small compared to the beam momentum the best way to express this is by integration over the width. The result is

$$\int \sigma \, dE = 30 \times 10^{-30} \text{ cm}^2 \cdot \text{MeV}.$$

The reaction is therefore much more competitive with strong interacts than is w^- production with other strongly interacting particles. At present accelerators a search up to 4 GeV w^- meson seems feasible.