when the potential is not separable have been discussed elsewhere.[3]

We should like to thank Professor H. P. Noyes for several communications concerning these questions.

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[5]We consider only the single-channel case for simplicity. The extension to the multichannel case is straightforward (see reference 3).

[6]We assume, of course, that the partial-wave amplitude, $V(k,k)$, of the potential is nonzero. See references 1 and 3 for a discussion of the cases when this is violated.

[7]We have assumed that $V(p,q)=V(q,p)$, which implies that $T_k(p',p)=T_k(p,p')$. Reference 3 includes a complete discussion of the unsymmetrical case.

SEARCH FOR INTERMEDIATE VECTOR BOSON PRODUCTION IN NUCLEON-NUCLEON COLLISIONS*

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Neutrino experiments carried out at CERN[1] and BNL[2] have indicated that the mass of the intermediate vector boson, the W, must be greater than 2 BeV. This lower limit is essentially set by the low yield of high-energy neutrinos available from present accelerators. It appears, however, feasible to search for the W produced in nucleon-nucleon interactions. This process can yield W's of mass up to 3.3 BeV with the proton energy available at the Argonne zero-gradient synchrotron (ZGS). Recent theoretical calculations[3] indicate that the cross section for W production is of the order of 10^{-6} of geometric. This cross section taken with a branching ratio of $\frac{1}{3}$ to the channel $W \rightarrow \mu + \nu$ gives a flux of muons at large momentum and angle (4-6 BeV/c at ~20° lab angle) which is significantly above the unavoidable background of muons from other processes. We have conducted an experiment to detect W production in nucleon-nucleon interactions which is sensitive to W masses in the range of 2 to 3 BeV. We find no muon signal in excess of that due to π and K decay.

The experimental apparatus used is shown schematically in Fig. 1. A proton beam of 12.5-BeV/c momentum (2×10^9/pulse) was incident on a 3-in.-long uranium target. In this parasite extracted proton beam, about $\frac{1}{2}$% of the circulating beam of the ZGS is spilled during the 250-msec flat top. The beam spot, 1 cm in diameter, was continuously observed by a closed circuit TV-scintillator system. The incident proton intensity was calibrated by gold-foil activation and monitored throughout the run by a triple telescope located at 150° production angle. A magnetic spectrometer viewed the target at a lab angle of 20°. This

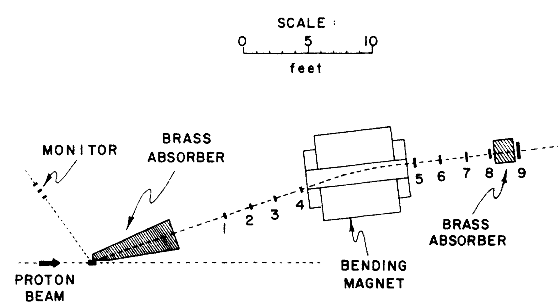

FIG. 1. Layout of experimental apparatus. Numbers 1 through 9 indicate plastic scintillator counters. Counters and the target are not to scale.

spectrometer, composed of entrance and exit four-fold scintillator telescopes, has an acceptance solid angle of 2.8×10^{-4} sr and a momentun resolution of 22% (full width at half-maximum). A massive shield was located adjacent to the target to suppress strongly interacting particles. Some additional discrimination against strongly interacting particles was obtained by the addition of a 430-g/cm^2 absorber and a ninth counter to the exit arm of the spectrometer. Not shown on Fig. 1 is a large amount of additional lead shielding employed to reduce single rates and to stop high-energy muons coming from the general direction of the accelerator.

Inasmuch as this method of detecting W's involves the observation of a very small muon signal, it is necessary to suppress all strongly interacting particles by at least a factor of 10^5 and to minimize the decay of pions and kaons into muons. This would imply the use of a shielding material with the shortest possible interaction length; however, such high-Z material results in excessive scattering which tends to cause the particles produced more copiously at smaller angles to be scattered toward the spectrometer. We chose brass as the best compromise for shielding material. The maximum shield length must be less than the range of muons to be expected from the decay of W's.

In order to be sure that we were detecting only muons in the spectrometer, we varied the thickness of the brass shield. Figure 2(a) shows an absorption curve obtained for 4-BeV/c negative particles from the target. It is seen that after 1800 g/cm^2 of brass there is no further exponential absorption. With a shield of this thickness the eight- and nine-fold coincidence rates became identical. The zero-absorber point gave us an absolute calibration for 20° pion production. This combined with an interaction length obtained from the absorption curve enables one to calculate the residual muon level. The agreement of this level and the observed yield is strong evidence that we are detecting only muons from pions. Figure 2(b) shows the comparison between the measured and calculated muon spectra for an absorber thickness of 1840 g/cm^2. The momentum values refer to the initial momentum of particles emerging from the target. The departure of the observed points from the calculated curve at low momenta is due to the effects of the range cutoff and finite momentum resolution.

The agreement between the calculated and measured muon spectra is very good and indicates that there is no large contribution of muons from sources other than pion decay; however, the scattering effects and secondary production in such a thick absorber are difficult to account for precisely. These difficulties are circumvented by another method, in which one varies the material near the target, changing the interaction length in such a way as to increase the yield of muons. The first 30 cm of brass was replaced by sixteen 6-mm lead plates spaced 12 mm apart. This leaves the number of radiation lengths in the shield unchanged. A measurement was then performed

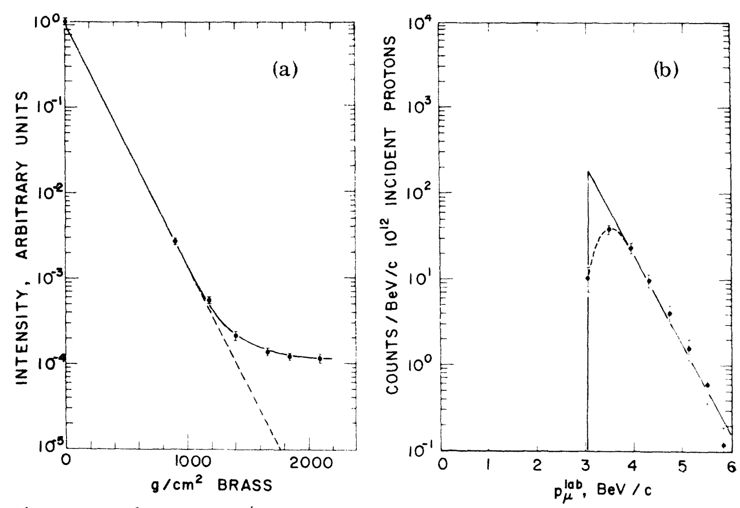

FIG. 2. (a) Absorption curve for 4-BeV/c negative particles from the target. The points are experimental intensities measured by varying the thickness of the absorber. The solid curve is the fit to the data. (b) Muon spectrum at 1840 g/cm^2 absorber thickness. The solid curve is the calculated muon spectrum from π decay. The cutoff near 3 BeV/c is the range cutoff of the absorber.

with the same substitution at the downstream end of the shield. The over-all absorption of the shield is unchanged in these two measurements. The net difference of these two measurements is due only to a signal from π and K decay. Using this result it is possible accurately to subtract those muons due to π and K decay from the data shown in Fig. 2(b). The result of this subtraction is shown in Fig. 3 expressed in units of $d^2\sigma/d\Omega dp$ per uranium nucleus. The errors shown are statistical.

The result is consistent with zero yield of muons from sources other than pion and kaon decay. The result can be expressed as an upper limit of the product of W-production cross section times the branching ratio for W decay into a muon. We find

$$(W \text{ production cross section})(\text{branching ratio}) \leq 4\times10^{-34}\ \text{cm}^2\ \text{sr}^{-1}\ (\text{BeV}/c)^{-1}\ \text{nucleon}^{-1}.$$

The number of effective nucleons in the uranium nucleus was estimated assuming an $A^{2/3}$ dependence.

A similar measurement was made for positive particles but the results are less sensitive due to the large inelastic-proton yield (several times the positive-pion yield).

The expected rates and equivalent cross section for muons from the reaction $p+n \to W^- + p + p$, $W^- \to \mu^- + \nu^-$ was calculated for different W masses using the production cross sections of Chilton, Saperstein, and Shrauner[3] and are shown in Fig. 3. A one-third branching ratio for this mode was assumed. Thus no boson production in the mass range of 2-3 BeV is seen if one assumes the cross sections as calculated by Chilton, Saperstein, and Shrauner. Confidence levels, calculated from χ^2 analysis of Fig. 3, for the nonexistence of the W of mass 2.0, 2.5, and 3.0 BeV are 99, 97, and 60%, respectively.

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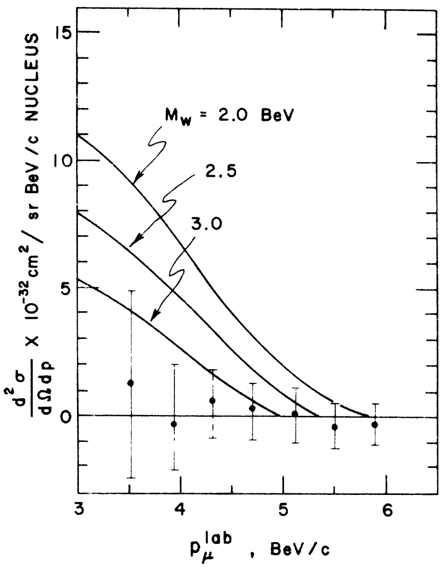

FIG. 3. The points are the momentum spectrum of the muons when the $\pi+K$ decay background has been subtracted in the manner described in the text. The solid curves are calculated from the production cross sections of Chilton, Sapertstein, and Shrauner.

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