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SEARCH FOR INTERMEDIATE BOSONS IN PROTON-NUCLEON COLLISIONS*

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We have carried out a measurement of the yield of high-energy muons emitted at large angles to a beam of 20- and 30-BeV/c protons at the AGS. Our objective was to set an upper limit to the production and decay probability of massive unstable states decaying into muons. The most interesting candidate for such a state is the intermediate boson W, supposed to mediate weak interactions. It has been recognized[1] that one important signature for a heavy W is the large transverse momentum given to the muon in the decay process

$$W \rightarrow \mu + \nu. \tag{1}$$

Recently, high-energy neutrino experiments have established that $m_W > 2$ BeV.[2,3] Thus, for a W of mass 2-6 BeV, the transverse momentum of the emitted muon can vary from 1 to 3 BeV/c. This is much larger than is typically found in secondary particles emerging from high-energy interactions. Furthermore, the conventional parents of muons, pions and kaons, can be largely "turned off" because of their relatively fast absorption by strong interactions in dense matter (~10 cm in tungsten) as compared to their mean free path (550 m at 10 BeV) for decay. Thus, the rate of muon counts observed at large angles, relatively easily reached by W decay, is an upper limit to $\sigma_W B$, where σ_W is the boson-production cross section for AGS protons (per nucleon), and B is the unknown partial rate for Reaction (1).

Figure 1 illustrates the experimental arrangement. The fast-extracted proton beam of the AGS was transported in a vacuum pipe up to the 82-ft steel shield of the Brookhaven National Laboratory (BNL) neutrino facility. An 18-in. block of Hevimet (90% tungsten) absorbed

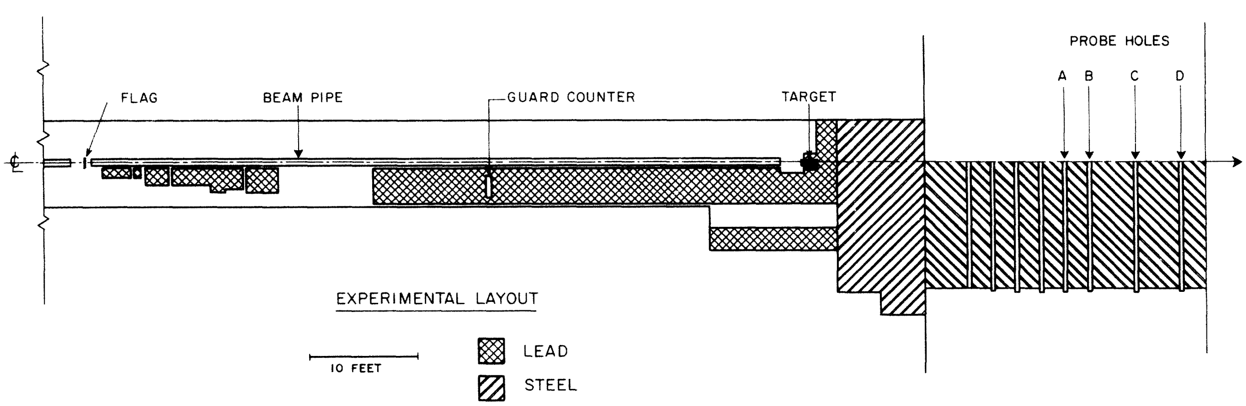

FIG. 1. Experimental apparatus.

the bulk of the beam and its secondary particles. Muons were counted by detectors inserted in 3-in.×3-in. holes located in the steel shield at ranges corresponding to muon momenta greater than 9.6, 11, and 12.5 BeV/c. The very short "on time" of the AGS extracted beam dictated the variety of counters employed. The flux from 0° out to about 5° was measured by integrating solid-state detectors. The linearity of these detectors, and associated amplifiers and digitizers, was verified over a counting rate range of from 10^3 counts/pulse down to 2 or 3 counts/pulse. The absolute calibration is only roughly known.

The region from ~4° to 9°, where the counting rates were below a few counts/cm^2 pulse, was measured by a 1-cm^2 telescope of two scintillation counters separated by 0.5 in. of Pb. At larger angles a 30-cm^2 telescope was used to improve the data-taking rate. Detectors in all three holes were operated simultaneously. All counters were gated by the rf structure (the gates being a train of twelve 30-nsec pulses separated by 200 nsec and generated by a Čerenkov counter viewing the target). A guard counter effectively monitored the positioning of the external beam by counting secondaries generated by the halo around the proton beam. It was adjusted to veto counts if the beam drifted more than ~$\frac{1}{2}$ in. off center in the 3-in.-diameter part of the vacuum pipe by locating it within a shield of about 30 ft of lead. This was stacked so as to screen the muon counters from any spray generated far upstream by beam halo (hitting flanges, etc.) and by interactions in an air space (20 mg of air plus Mylar) separating the machine vacuum from the beam-transport system.

Muons were counted in each of the three holes and over an angular range from 0° to ~12°. Two proton-beam energies were used to cover the W-mass range from ~2 to ~6 BeV. The results are presented in Fig. 2. The lower curves give the raw data except that the solid-state points were normalized to join smoothly to the small telescope near 4°. A comparison of these points with the yields expected from an intermediate boson limits the product $\sigma_W B$ to the order of $(3\text{-}4)\times10^{-34}$ cm^2 for the mass range 3-6 BeV (see Fig. 3). However, it is obvious from a straightforward extrapolation of the curves that most of the counts are muons from pions and kaons. This is further borne out by a calculation of the expected yields, using beam survey results from BNL, CERN, and earlier emulsion data from the neutrino runs.[3] Multiple scattering was included in the form of a Gaussian with an rms parameter of 15 in. The agreements [broken curves shown in Fig. 2(c) and 2(f)] are well within thick-target uncertainties.

Finally, experimental tests were carried out in order to perform a quantitative subtraction.

(1) Moving target effect.—4 in. (about 1 mean free path) of Hevimet could be remotely moved through a distance of 1.5 ft. Since about half the muons observed come from pions and kaons emerging from ~1 mean free path, these now have a flight path for decay which can be varied from ~10 cm (in Hevimet) to 45 cm (in air). In Fig. 2 the upper curves represent the distribution of muons amplified by target motion. It is clear that most of the muons observed are from long-lived parents. W muons would be affected only in higher order by the motion.

Let $N_\mu(d, L)$ represent the yield observed at a distance d from the axis of the beam with the movable 4 in. of the target at L feet from the remainder. Then the yield of muons at a depth D in the shield originating from a rapidly decaying source ($\tau \lesssim 10^{-9}$ sec) can be shown to be

$$Y_W(d',0) \leq N(d',0) - \left[\frac{N(0,0)}{N(0,L)-N(0,0)}\right] \times \{N(d,L)-N(d',0)\}, \qquad (2)$$

where $d' \cong (1-L/D)d$.

This permits an experimental subtraction based upon the following assumptions: (i) The muons observed near 0° are all from pions and kaons. This gives the experimental amplification of muons from long-lived parents due to target motion. (ii) This amplification is independent of production angle. A correction must be made for the change in angle at a given position due to the extra 1.5 ft (out of 34 ft for hole D). The subtraction is of course limited by statistics and the intervention of several small corrections [hence the inequality in Eq. (2)] which are sensitive to details of the production mechanism.

(2) Upstream source effect.—Earlier runs indicated that above 10°, a "background" appears which was traced to ~0.1 g/cm^2 of material in the beam (flag) at about 75 ft from the shielding wall. Particles emitted at small angles from this point simulate muons emitted at ≳10° from the Hevimet. To minimize this, the upstream material was reduced to a minimum

of ~30 mg/cm^2 and lead shielding was added as shown in Fig. 1. Both steps resulted in a reduced background. Flags of 150 mg/cm^2 could be remotely inserted both here and further upstream where the air gap between AGS vacuum and transport vacuum was located. The shape of the flag-in data strongly suggests that counts above 10° (which at 30 BeV/c has a character-

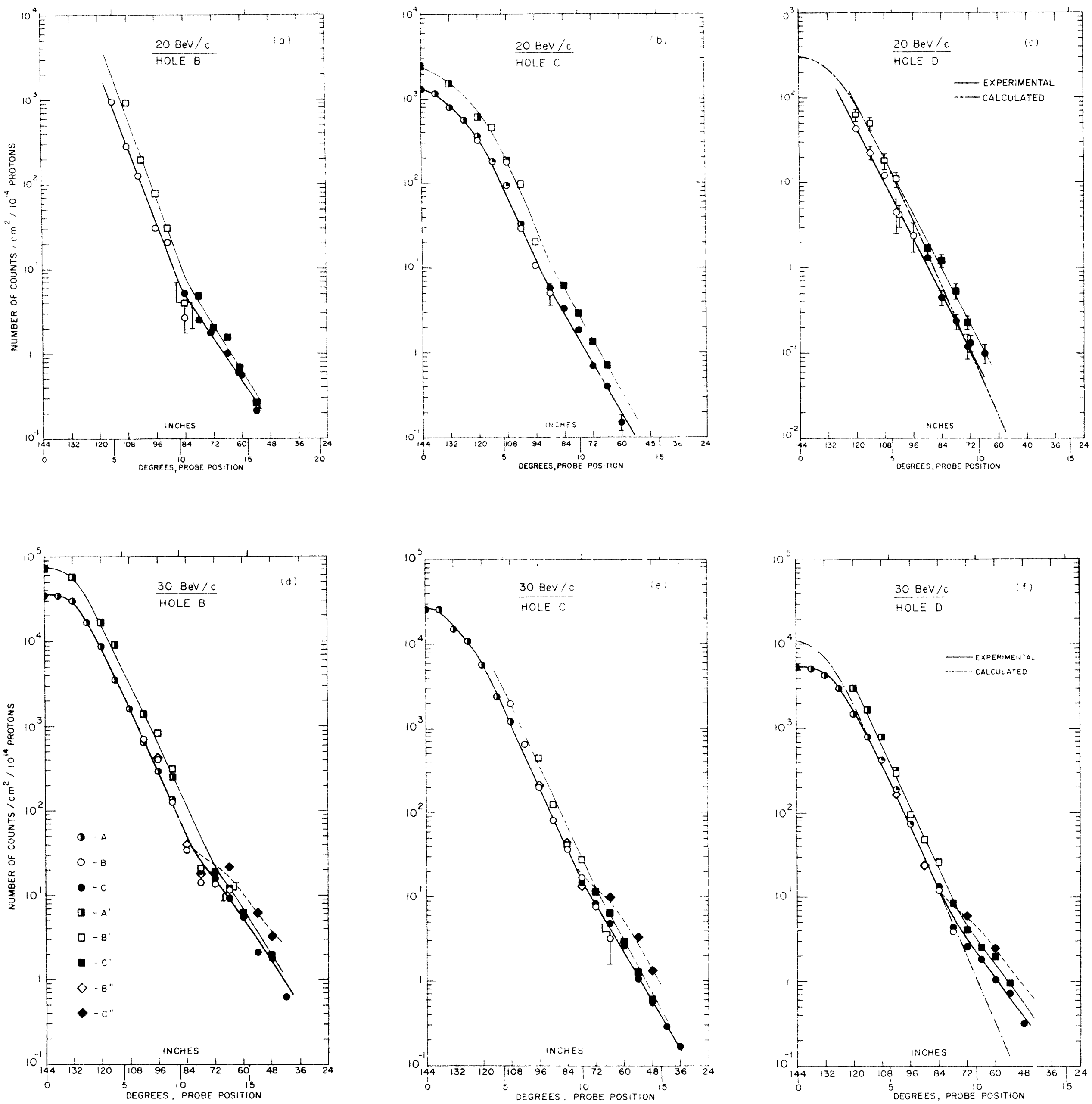

FIG. 2. Experimental results. Figures 2(a), 2(b), and 2(c) are 20-BeV/c produced muons of energy greater than 9.6, 11.0, and 12.5 BeV, respectively. Figures 2(d), 2(e), and 2(f) are the same for 30-BeV/c protons. Symbol A, solid-state detection; symbol B, small telescope; symbol C, large telescope; symbols A', B', and C' correspond to target moved to 1.5-ft position; symbols B'' and C'' are with upstream flag "in." The statistical errors when not shown are smaller than the symbol. The solid curves are drawn through the experimental points. The dot-dash curves in Figs. 2(c) and 2(f) are calculated from beam survey data. The dashed curves [Figs. 2(d), 2(e), and 2(f)] are drawn through the "flag-in" data.

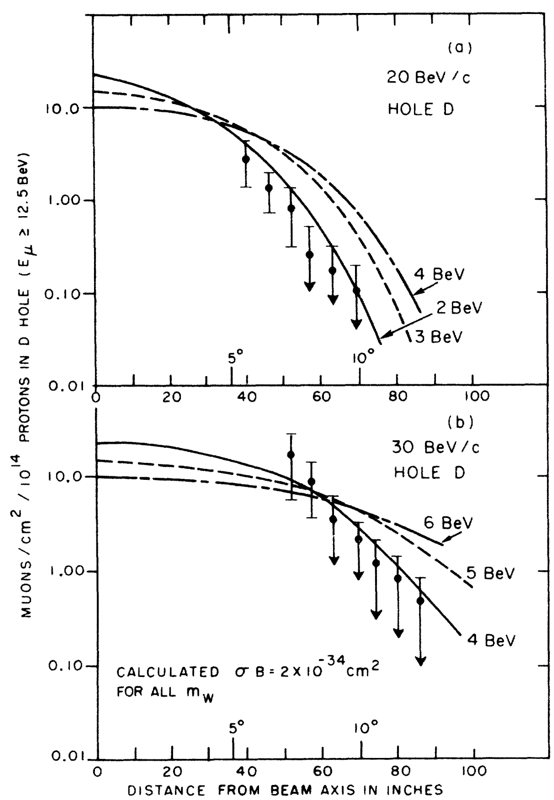

FIG. 3. Subtracted results and calculation of muon flux from W's. The W yields are all normalized to $\sigma_W B = 2\times10^{-34}$ cm^2. In hole D, $E_\mu \geq 12.5$ BeV. (a) AGS proton-beam momentum 20 BeV/c, $m_W = 2$, 3, and 4 BeV; (b) AGS proton-beam momentum 30 BeV/c, $m_W = 4$, 5, and 6 BeV.

istic change in slope) are indeed upstream muons. A minimum subtraction may be made by assuming that the maximum upstream-source effect comes from the 30 mg/cm^2. Since there are many additional possibilities, i.e., beam halo impacting on flanges, etc., this gives an upper limit to the residual muon count. This correction was negligible at 20 BeV/c.

The data used here came from 30 hours of AGS running and were duplicated in an earlier run differing in counter construction and shielding details. This gave similar results with somewhat reduced sensitivity. In Fig. 3 we present subtracted data for $E_\mu \geq 12.5$ BeV and for the 20- and 30-BeV/c proton runs, together with results of a calculation of muons from W decay. The statistical upper limits of the subtracted points are rarely more than a factor of two less than the original points. The treatment of both effects above has been such that a minimum subtraction has been made. Consequently, the lower half of the error bars have been arbitrarily extended.

The possibility of strong production of W's was suggested by Lee and Yang.[4] However, the very high momentum transfer and multitude of available channels makes a detailed calculation of massive W production uncertain by several orders of magnitude.[5] Similarly, the partial decay rate into leptons cannot be reliably calculated for a heavy boson.[6] Consequently, we have treated the problem in the following ways: (a) Assume all W's are produced at 0° with a total cross section per nucleon of σ_W. These decay promptly and isotropically in their c.m. system to muons, with a branching ratio B. The multiple scattering of the W muons is treated with the same program as the π-K muons. (b) A somewhat more realistic calculation makes use of a model to calculate the angular distribution of W's. The σ_W is factored into a nucleon-nucleon total cross section, a semiweak vertex, and a nucleon propagator term. In the latter an exponential suggested by Yang and Wu was used.[7]

The results were arbitrarily normalized to $\sigma_W B = 2\times10^{-34}$ cm^2 and appear in Fig. 3. These are only slightly broadened relative to those of Method (a). It is important to note that, because we are comparing angular distributions of muons from W's with experiment, the results are quite model independent. This is because near threshold the W must go forward, and above threshold the W presumably wants to be produced with the smallest possible momentum transfer. The results based upon a statistical confidence level of $\geq 99\,\%$ are presented in Table I. We conclude from this that for proton-nucleon collisions and in the mass range from ~2.5 to ~6 BeV,

$$\sigma_W B < 2\times10^{-34}\ \text{cm}^2\ \text{(99\% confidence level)}.$$

Table I. Upper limit of $\sigma_W B$ as a function of mass of W.

Proton momentum (BeV/c)	Mass of W (BeV)	Upper limit of $\sigma_W B$ (cm^2)
20	2	3×10^{-34}
20	3	2×10^{-34}
20	4	1×10^{-34}
30	4	4×10^{-34}
30	5	2×10^{-34}
30	6	2×10^{-34}

Table II. Relative phase space for W production.

Final state	M_W (BeV) 2.5	3	4	5	6	7
Proton momentum 30 BeV/c						
$N+N+W$		1	0.8	0.6	0.4	0.15
$N+N+W+\pi$		1	0.75	0.48	0.25	0.04
$N+N+W+2\pi$		1	0.65	0.35	0.12	···
Proton momentum 20 BeV/c						
$N+N+W$	1	0.95	0.72			
$N+N+W+\pi$	1	0.85	0.47			
$N+N+W+2\pi$	1	0.74	0.31			

Since each proton makes many pions, similar limits apply to pion-nucleon collisions averaged over pion spectra characteristic of the AGS. Antiproton or K-nucleon cross-section limits are reduced roughly as the yields observed in secondary beams. It should be emphasized that this experiment integrates over all possible final states. In order to get some estimate of the sensitivity to mass, we have given in Table II the relative phase space for typical final states, using 20- and 30-BeV/c protons incident on nucleons having Fermi motion.

It is seen that the 20-BeV/c run is reasonably sensitive to 4-BeV bosons, and the 30-BeV/c run extends to a mass of 6 BeV. Clearly, the interpretation of these data in terms of the existence of bosons of $m_W < 6$ BeV must await a better theoretical grasp of the problem of production of heavy particles.

Finally, we note that one can speculate on other reactions leading to large-angle muons. For example, π^0 photons can produce wide-angle muon pairs or perhaps heavier leptons. Further refinements of this type of measurement would have to contend with these sources.

We would like to thank M. L. Good for suggestions and T. Novey for information on a similar experiment being carried out at Argonne.[8]

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