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EXPERIMENTAL DETERMINATION OF BRANCHING RATIOS OF VECTOR MESONS INTO LEPTON PAIRS*

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The decay of neutral vector mesons ($V^0 = \rho, \varphi, \omega$) into leptons ($l = \mu$ or e) has been studied in the reaction $\pi^- + p \to n + V^0$ with the subsequent decay $V^0 \to l^+ + l^-$ at the Brookhaven National Laboratory AGS using a system of scintillation counters and spark chambers. Previous experiments[1] have placed upper limits on the decay $V^0 \to l^+ + l^-$. Our measured branching ratios are a factor of 10 lower than the previously measured upper limits for the electron decay modes. The importance of measuring these leptonic decay modes has been recognized for some time.[2]

Figure 1 shows the experimental arrangement. A pion beam of 3(±1%) BeV/c was incident on a liquid-hydrogen target. The experiment measured the opening angle of a pair of particles electronically identified as leptons. The distribution of opening angles is strongly correlated to the mass of the parent system. A 24-in. ×24-in.×4.5-in. spark chamber (T) registered the tracks of the lepton pair before appreciable material was encountered. All counters were segmented into a quadrant array about the beam axis as shown in the upper part of Fig. 1. Counters B and B^* were each preceded by $\frac{1}{4}$-in. lead sheets, and A, B, and B^* were interrogated for pulse height to identify an electron shower. The relative pulse-height distribution to discriminate against pions, to better than 1 part in 100, was determined by previous calibration

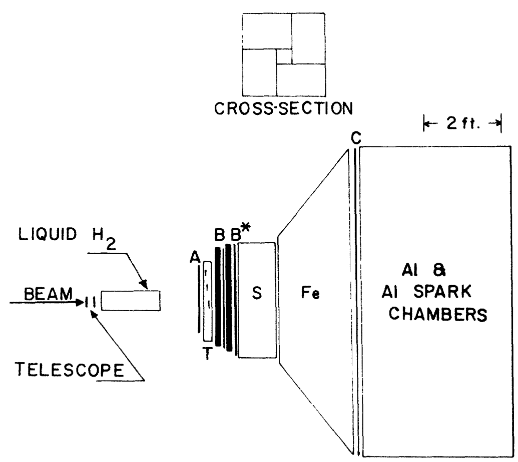

FIG. 1. Experimental arrangement.

over the energy range 0.5 to 2.0 BeV. (Thus, we discriminate against pairs of pions by a factor of more than 10^4.) The chambers marked S contained 8 radiation lengths of lead and scintillators, and the pulse height from these counters was proportional to the total energy of an electron passing through S. The pulses[3] from S were photographed from oscilloscope traces. A trigger required that signals from any two quadrants of A, B, and B^* simultaneously satisfied predetermined pulse-height levels. The remaining portion of the system separated muons from pions. This consisted of 4.4 in-

Table I. Processes considered in generating Monte-Carlo events.

Process[a]	Cross section[b] (mb)	Reference
$\pi^- + p \to \pi^- + p$	6.8	c
$n + \eta$	0.05	d
$n + \rho^0$	1.6	e, f
$n + \omega$	0.5	d, g, h
$n + \varphi$	?	
$n + f^0$	0.32	e, f
$N^* + \pi + \pi$	0.8	f
$N + \pi + \pi$	0.8	f
$N + \pi + \pi + \pi$	0.9	f
$p + \rho^-$	0.7	f
$\Sigma^0 + K^0$	0.086	i
$\Lambda^0 + K^0$	0.031	i
$\Sigma^- + K^+$	0.015	i
$n + \pi^0$	0.3[j]	k

[a]N represents either neutron or proton.

[b]Branching ratios to various modes are from A. Rosenfeld et al., Rev. Mod. Phys. 36, 977 (1964), except where explicitly stated.

[c]W. Selove, private communication.

[d]W. Bugg, private communication. Branching ratio to Dalitz pairs from T. Fulton, private communication; and D. Bessis, M. Jacob, and A. Morel, Nuovo Cimento 30, 112 (1963).

[e]W. Selove, V. Hagopian, H. Brody, A. Baker, and E. Leboy, Phys. Rev. Letters 9, 272 (1962).

[f]V. Hagopian, private communication.

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[h]U. Kruse, private communication.

[i]T. Wangler, A. Erwin, and W. Walker, Phys. Rev. 137, B414 (1965).

[j]mb/sr at 0°.

[k]M. Wahlig, I. Mannelli, L. Sodickson, O. Fackler, C. Ward, T. Kan, and E. Shibata, Phys. Rev. Letters 13, 103 (1964).

teraction lengths of iron and aluminum, as well as eight large Al spark chambers.[4] The pion reduction from this amount of material was also calibrated over the above energy range.

Data reduction required proper energy deposit in two and only two S-chamber quadrants, two tracks in T in corresponding quadrants, and reconstruction of the measured tracks to a common vertex in the target.

We now restrict the discussion to electron-pair events. A Monte-Carlo program was used to generate the opening angle of events accepted by the experimental system. The efficiency

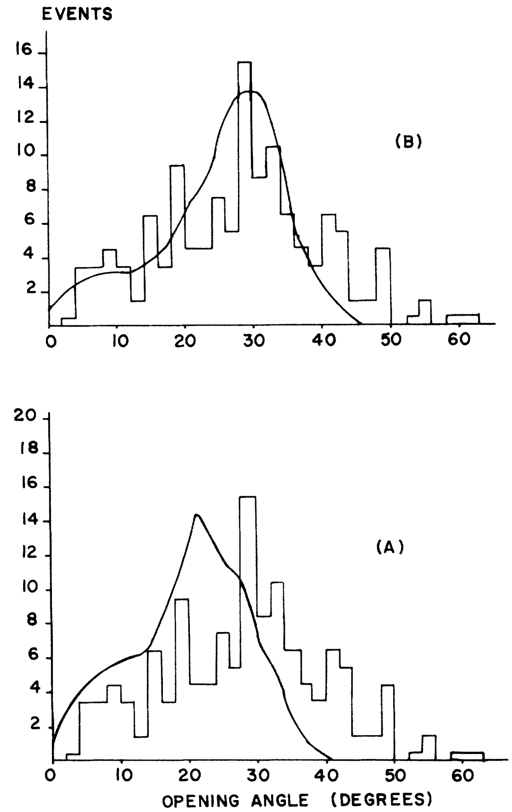

FIG. 2. Histogram of electron data as a function of the opening angle of the pair. The Monte-Carlo curve in (a) contains only background processes; in (b) the processes $\rho \to e^+ + e^-$ are included with background.

with which the events were observed was obtained by considering the geometry of the system, the calibrated efficiency of the counter arrays, and the angular distributions and cross sections of the processes considered. Table I shows the processes considered. Figure 2(a) shows a Monte-Carlo curve generated for our experimental setup, assuming that only background processes contribute, and a histogram of the data with a 10% target-empty correction. If we include in the Monte-Carlo calculation the decay of the ρ and ω mesons into electrons, the curve in Fig. 2(b) is generated. Since we are unable to separately identify ρ and ω events,[5] we determined only the sum $(a\rho + b\omega)$. In assigning the ratio a/b, we assume the photon to be a member of a unitary-spin octet and the ω-φ mixing angle[6] to be 38°. The above assumptions (together with experimental efficiencies of the counter arrays as determined by calibration and cross sections detailed in Table I) yield

$a/b = 3$. There is still an excess of data at large opening angles which is unexplained by the assumed processes. The mass associated with these large-angle events is near 1 BeV. If we assume this parent particle to be the φ and its production angular distribution to be similar to that of the ω, $(1+\cos\theta)$, we obtain the Monte-Carlo fit shown in Fig. 3. This fit (which includes an ω-φ mixing angle of 38°) yields the branching ratios

$$\frac{\rho \to e^+ + e^-}{\rho \to 2\pi} = (0.5^{+0.6}_{-0.3}) \times 10^{-4},$$

$$\frac{\omega \to e^+ + e^-}{\omega \to 3\pi} = (1.0^{+1.2}_{-0.8}) \times 10^{-4},$$

and

$$(\text{Branching ratio} \times \text{cross section})_{\varphi} = (2.9 \pm 1.5) \times 10^{-4} \text{ mb}.$$

We are able to quote only the product of the branching ratio and cross section for the φ. If the production angular distribution of the φ is characteristic of ρ, the product $(R \times \sigma)$ is reduced by a factor of 2.[7]

The extent of the variation of results on changes in the mixing angle is demonstrated by allowing a zero-degree mixing angle ($\omega_8 = \varphi$). Then

$$\frac{\rho \to e^+ + e^-}{\rho \to 2\pi} = (0.65^{+0.8}_{-0.4}) \times 10^{-4}.$$

The fact that the Monte-Carlo calculation for our experimental apparatus gives an identical opening-angle distribution for the background events and for the vector-meson decays into muon pairs prevents us from separating muon events from pion events on the basis of the experimental data. However, our electronic muon trigger required two particles to have passed 4.4 interaction lengths of iron and aluminum, in addition to giving energy deposits in the S chamber (see Fig. 1) consistent with muons. (The interaction length and the energy deposit in the S chambers over the energy range of the secondaries had been determined by previous calibration at the AGS.) From the number of muon triggers observed we are able to place upper limits on the muon branching ratios of 10 times the corresponding electron branching ratios. For instance,

$$\frac{\omega \to \mu^+ + \mu^-}{\omega \to 3\pi} \leq 10^{-3}.$$

These results are in agreement with published results on the muonic branching ratios obtained from the analysis of bubble chamber data. Complete reconstruction of the muon events, as described above, yield the opening angular distribution expected on the basis of our Monte-Carlo calculation.

We wish to acknowledge many helpful and encouraging discussions with Professor G. Feldman, Professor T. Fulton, Professor A. Pevsner, and Dr. G. Kane. We also want to thank Dr. R. Shutt and members of the staffs of the AGS and Johns Hopkins who were instrumental in the execution of this experiment. Finally, we are especially indebted to the Olin Mathieson Chemical Corporation for the aluminum ingots which were used for absorbers in this experiment.

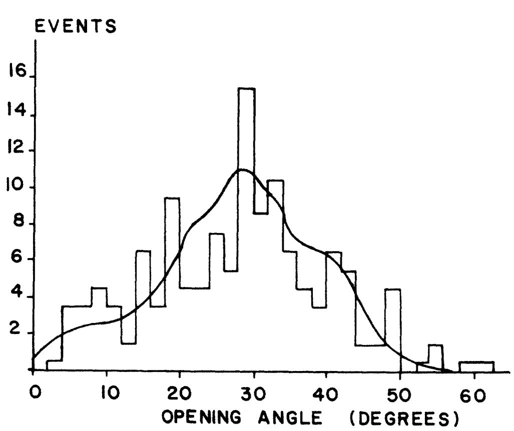

FIG. 3. Histogram of electron data with Monte-Carlo curve giving best fit.

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[2]G. Feldman, T. Fulton, and K. C. Wali, Nuovo Ci-

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[3]Each of the four S chambers was observed by 10 phototubes. These phototubes were optically isolated, and each observed 0.8 radiation length of the S chamber. The 10 signals were added electronically, and the sum pulse had been established experimentally to be proportional to the energy of an electron passing through the S chamber.

[4]We wish to thank the Columbia-Brookhaven neutrino group for the loan of the Al spark chambers.

[5]The separation of ρ and ω events is analogous to the separation of the two-pion decays of those particles. This has proved to be extremely difficult. An experiment of high statistical significance may be able to separate these events experimentally if the mass resolution is <10 MeV. If a mixing angle near 38° is correct, then SU(3) would predict nearly equal branching ratios for ρ and ω.

[6]J. J. Sakurai, Phys. Rev. Letters 9, 472 (1962).

[7]If we assume a φ cross section of 50 μb, then the branching ratio of φ to electron pairs is $R(\varphi \to e^+ + e^-) = (6 \pm 3) \times 10^{-3}$.

MUON-PROTON SCATTERING AT HIGH MOMENTUM TRANSFERS*

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We report in this Letter the result of an experiment to observe the scattering of muons by protons at high momentum transfers. A comparison of the results with similar electron-scattering data provides a sensitive test of any presumed difference in the charge structure of the leptons. The data reported here consist of about 500 scattering events with momentum transfer in the interval 700 to 1100 MeV/c. They indicate no significant difference between μ-p and e-p scattering. This is in agreement with earlier studies,[1,2] but extends considerably the limits on any presumed anomaly.

The experiment was performed at the Brookhaven AGS, using the experimental arrangement shown in Fig. 1. A specially designed internal target ($G9$) permitted negative pions produced near 0° to be deflected out of the machine by one section of the AGS magnet ring. Pions of 6- to 10-BeV/c momentum were accepted and transported for a distance of about 170 ft by a 14-quadrupole magnet array. The decay muons were then separated from the pions by transmission through a concrete filter filling the first 32 ft of an iron collimator 45 ft in length. The transmitted muon beam had a momentum spectrum extending from approximately 1.5 to 6.0 BeV/c (peaked at 2.8 BeV/c), an angular divergence of less than 1°, and an intensity of about 2×10^6 per pulse for a flux of 3×10^{11} protons per pulse. From our measurements[3] of the nuclear attenuation of pions in concrete, we estimated that the ratio of pions to muons transmitted by the filter was less than 10^{-6}. This estimate of the contamination was corroborated by direct measurements (see below).

The detectors consisted of an array of scintillation counters and spark chambers. Incident muons were counted by a gas Cherenkov counter (C) 12 in. in diameter, and by a 10×10-in. scintillation counter (S), and were then incident on a liquid-hydrogen target 72 in. long and 18 in. in diameter. Scattered muons traversed one or both of a pair of aluminum plate spark chambers (Mu-1 and Mu-2), a 40-ft-thick heavy concrete absorber, and a liquid scintillation