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[1]C. B. Chiu and J. D. Stack, Phys. Rev. 153, 1575 (1967).

[2]B. Barger and D. Cline, Phys. Rev. Letters 21, 392 (1968).

[3]E. A. Paschos, Phys. Rev. Letters 21, 1855 (1968).

[4]R. Anderson et al., Phys. Rev. Letters 21, 479 (1968).

[5]G. E. Fischer and Y. Murata, Stanford Linear Accelerator Center Report No. SLAC-PUB-605, 1969 (unpublished).

[6]Stanford Linear Accelerator Center User's Handbook (unpublished), Sec. E; W. K. H. Panofsky, in Proceedings of the International Symposium on Electron and Photon Interactions at High Energies, Hamburg, Germany, 1965 (Springer-Verlag, Berlin, Germany, 1965), Vol. I.

[7]A. Boyarski, Stanford Linear Accelerator Center Report No. SLAC-PUB-559 (to be published).

[8]E. W. Anderson et al., Phys. Rev. Letters 22, 102 (1969).

[9]C. Botke, "Partial-wave analysis of $\pi^- + p \to \eta + N$" (to be published).

[10]S. R. Deans and J. W. Wooten, "Spin-2 exchange in the process $\pi^- + p \to \eta + N$ and the η-nucleon coupling constant" (to be published).

[11]This argument was presented in a talk by G. Kane at an informal meeting on backward processes held at SLAC, January, 1969.

[12]A. T. Davis and R. G. Moorhouse, Nuovo Cimento 52A, 1112 (1967).

[13]R. Dashen and S. Y. Lee, Phys. Rev. Letters 22, 366 (1969).

SEARCH FOR THE INTERMEDIATE VECTOR BOSON*

P. J. Wanderer, Jr., R. J. Stefanski, and R. K. Adair
Yale University, New Haven, Connecticut 06520

and

C. M. Ankenbrandt, H. Kasha, R. C. Larsen, L. B. Leipuner, and L. W. Smith
Brookhaven National Laboratory, Upton, New York 11973

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A search for the vector boson (W particle), postulated as the mediator of the weak interaction, has been carried out by determining the intensity and polarization of muons originating very near the point of interaction of 28-GeV protons with nucleons. Bosons were not observed and the upper limit on the production cross section for W's with masses between 2.0 and 4.5 GeV/c^2 is $B\sigma \lesssim 6\times10^{-36}$ cm^2, where B is the branching ratio for the W decay to a muon and a neutrino.

It is attractive in many respects to consider that the weak interactions might be mediated by a vector boson, the W. Although no reliable method of calculating the mass of such a particle has been found, the small value of the K_1^0-K_2^0 mass difference suggests[1,2] that the W mass is less than 5 GeV/c^2, and the unsuccessful searches[3] for the W in neutrino experiments indicate that the mass must be greater than 2 GeV/c^2—if the W exists at all!

Though it is difficult to produce W's with masses greater than 2.0 GeV/c^2 with the secondary neutrino beams presently available from accelerators, the production of W's with masses up to 5 GeV/c^2 is kinematically accessible through the interaction of the primary proton beams with target nucleons. An examination of typical diagrams for the production of W's, shown in Fig. 1, shows that the nucleon-nucleon production of W's might be expected to be about $(137)^2$ times as probable as neutrino production, even as two electromagnetic vertices in the diagram of Fig. 1(a) are replaced by strong-interaction vertices in Fig. 1(b), provided that the weak-interaction form factors for the (p, W, n) vertex are not very much smaller than the unit form factor for the (ν, W, μ) vertex. If this timelike form factor is quite small for values of the square of the momentum transfer $q^2 = -M_W^2$, then previous measurements[4] of the W production cross section, σ, which place a limit such that $B\sigma \leq 2\times10^{-34}$ cm^2, might not be regarded as strong evidence that a W with a mass in this range did not exist. Here M_W is the mass of the W and B is the branching ratio for the decay of the W into a muon and a neutrino. Indeed, an estimate of the form factor for W pro-

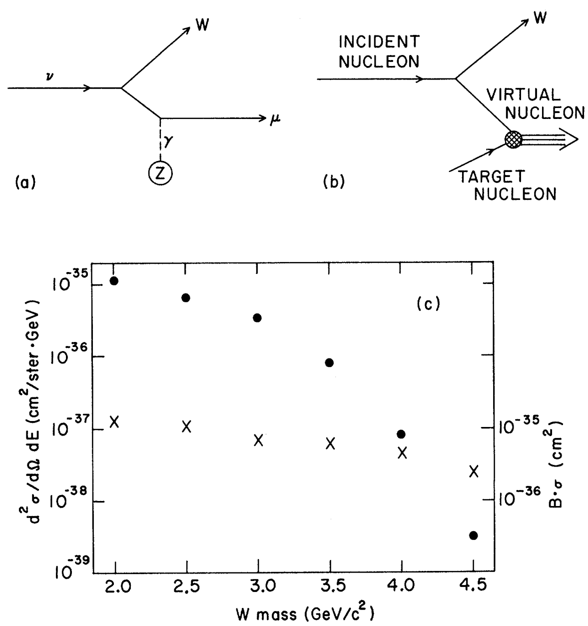

FIG. 1. Similar diagrams important in the production of W's. (a) W production by neutrinos. (b) W production in nucleon-nucleon interactions. (c) Predicted differential cross sections for the production of muons through W decays are shown as dots, referred to the left-hand scale. The W production was calculated for the diagram in (a) from the relations in the text and the branching ratio B was taken as $\frac{1}{4}$. The values are for muons with an energy of 25.1 GeV produced in the forward direction such that $1.0 \geqslant \cos\theta \geqslant 0.999$. The crosses, referred to the right-hand scale, represent the result of the experiment, a limit on the differential cross section, interpreted in terms of a limit on the total cross section through the aforementioned model for diagram (a).

duction using certain models of the form factor, together with the failure of previous experiments to detect muons produced electromagnetically, where the matrix elements are presumed very similar and the production cross sections are closely related,[5] suggests that these experiments were not, in fact, sensitive to W production. It then seemed important to us to attempt a more sensitive investigation of W production and, hopefully, to establish the existence of the W or to demonstrate that a W does not exist with a mass less than 5 GeV/c^2.

In the present experiment, illustrated schematically in Fig. 2, the 28-GeV slowly extracted proton beam of the Brookhaven alternating-gradient synchrotron was directed onto a target constructed of 1-in.-thick slabs of uranium which could be separated to vary the effective target density. Muons produced as a result of interactions in this target passed through a magnet packed with steel and through a thick steel shield to stop in a detector where the flux, polarization, and lifetime of the muons were measured. This detector was set at an angle of 3.5° with respect to the primary beam and the magnet served to direct muons of a definite charge, which were produced in the forward direction, into the dectector.

The detector was constructed in 23 sections, each consisting of a 4-in.-thick aluminum slab 2 ft wide and 3 ft high and a scintillation counter of the same area but $\frac{1}{4}$ in. thick. Muons which stopped in the detector precessed in a magnetic field applied perpendicular to the axis of the detector, which was aligned with the beam. The

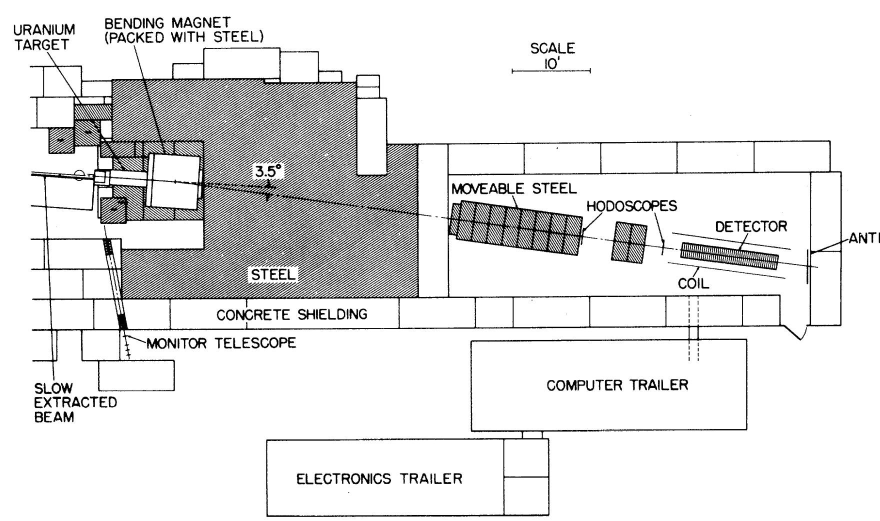

FIG. 2. Sketch of the experimental apparatus.

position of the muon stop along the axis of the detector was determined by those counters which indicated the passage of the muon, and the direction of emission of the positron from the muon decay and the time of this decay were determined by recording subsequent signals from these same counters. The component of polarization of the muon with respect to the beam direction was then determined through an analysis of the forward-backward ratios of the electron decays from the precessing muons as a function of time.

Coincident pulses from the two hodoscopes shown in Fig. 2 generated a trigger which caused the signals from the detector to be recorded and then transferred to a small on-line computer. A large anticoincidence counter behind the apparatus vetoed most particles which failed to stop in the detector.

Various tests on the data allow us to rule out many possible types of systematic errors: (a) The observed time distributions of decay electrons are a sensitive indicator of wrong-charge contamination because the negative-muon lifetime in aluminum is much shorter than that of the positive muons. No such contamination was observed in the distributions. (b) The ratio of observed delayed counts to stopping particles agrees with the electron escape probability that we calculated for μ-e decays in the aluminum slabs. (c) The angular distribution of incoming muons recorded by the hodoscopes did not change appreciably with the amount of "movable" steel in the beam. This indicates a negligible contamination of low-energy, wide-angle muons in the high-energy data.

The muons which stop in the detector could originate from three physically different sources. There should be a flux of muons produced in the primary interactions through electromagnetic production of muon pairs: These muons will not be polarized along the direction of the beam as the production process conserves parity. There should be an equal number of positive and negative muons produced from this mechanism. Muons may also be produced through the weak-interaction decay of very short-lived W vector bosons. In the center of mass of the W^+, positive muons will be polarized in the direction of their momentum: They will have positive helicity. Those muons which have very high energies in the laboratory system will retain this helicity. One also expects a flux of muons from those π and K mesons which decay before they are absorbed through interactions in the target and shield. These muons, which result from the weak-interaction decays of pseudoscalar particles, will have helicity opposite to that of muons from W decays. Furthermore, the flux of muons from this source will be proportional to the mean free path of the mesons in the target and then inversely proportional to the density of the target. It is well known that the interactions of high-energy protons produce many more high-energy positive mesons than negative mesons.

The contribution to the observed flux from each of the three sources of muon production can be determined in principle through the following procedures. The intensity and polarization of the muons can be measured as functions of the mean free path for mesons in the target, that is, as functions of the inverse target density. The value of the flux extrapolated to infinite target density corresponds to the contribution from the "prompt" electromagnetic processes and W decays and the polarization of this flux depends upon the proportion of the flux which results from W decays. If W's exist we expect comparable contributions to the flux from W decays and electromagnetic pair production.[5]

Such measurements of the flux and the polarization of the muons as functions of target density were made for muons with initial energies of 25.1, 23.5, 20.3, and 11.6 GeV, where the energy of muons which stopped in the detector was varied by changing the thickness of the shield. The flux measurements were corrected for interactions fore and aft of the uranium target, for the change of solid angle with target density, and for the "granularity" of the target. From the analysis of the kinematics of the reactions discussed below we believe that the most sensitive and significant test of the existence of W's will be derived from the measurements at the highest energies. The graphs of Fig. 3 show some of the most relevant results at 25.1 GeV.

The flux of muons defined by the intercepts of the curves of Fig. 3(b) at infinite target density is so small that the polarization of this sample is not well determined by extrapolation: The polarization of the muons produced at a target density of 1 (in terms of the density of uranium) is not sensibly different from the polarization of muons produced with a target density of $\frac{1}{3}$ [cf. Fig. 3(a)]. Since the muon-charge ratio varies with target density, it is clear that a substantial fraction of the extrapolated flux must result from a source other than the background expected from the decays of mesons produced by protons interacting in the beam-transport system, which should display the same charge asymmetry as the muons produced by meson decays in the target. An analysis of the results shown in Fig. 3(b) shows that the ratio of positive to negative muons produced from the decay of mesons in the target is 10.8; the flux of prompt muons symmetric in charge, which we attribute to the electromagnetic production of muon pairs, corresponds to a nucleon-nucleon production cross section of $(2.75 \pm 0.38)\times 10^{-35}$ cm^2/sr GeV per target nucleon and the remaining flux, which is probably due to the background from the scraping of the proton beam in the transport system, simulates a production cross section of $(1.6 \pm 0.9)\times 10^{-35}$ cm^2 sr GeV. There is no presumptive indication of a contribution from W production and we believe that a reasonable upper limit for W production can be taken 1.5×10^{-35} cm^2/sr GeV per target nucleon.

It is important to compare this experimental limit with some plausible model of W production and decay. For very high-energy W production we can presume that the production is dominated by processes described by diagrams such as that shown in Fig. 1(b), which is similar to dominant diagrams for the production of W's by neutrino interactions. We can calculate the cross section for the production of W's with a mass M_W, through the mechanism defined by the diagram 1(b) using the prescription of Chew and Low,[6] as a function of the square of the invariant mass of the virtual baryon, Δ^2, and the square of the invariant mass, ω^2, of the system of the virtual nucleon and the target nucleon. The cross section is then

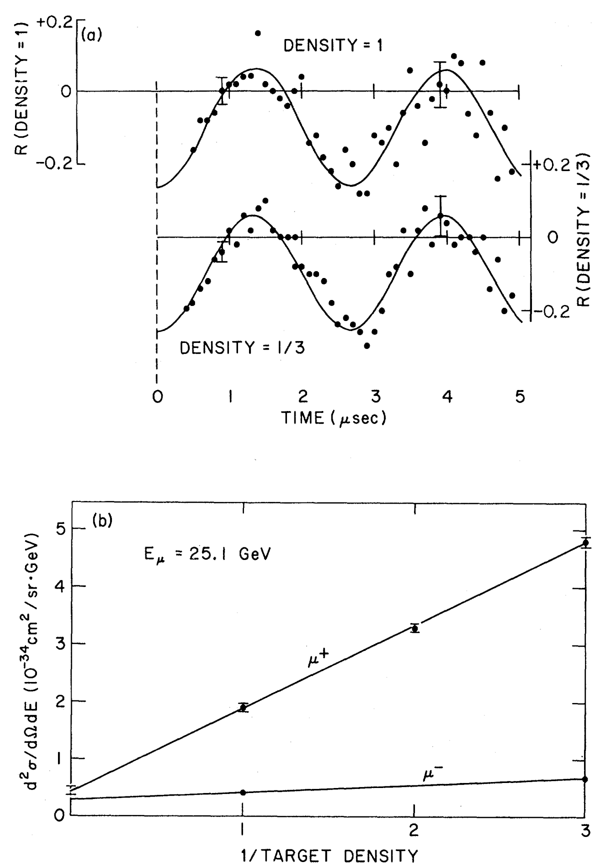

FIG. 3. (a) Plots of $R \equiv (F-B)/(F+B)$, where F is the number of decay electrons seen in the forward hemisphere (relative to the direction of the incoming muons) and B is the number seen in the backward hemisphere. R is proportional to the polarization. (b) Plot of the muon flux as a function of inverse target density. Errors for the μ^- curve are smaller than the data points.

$$\frac{d^2\sigma}{d(\Delta^2)d(\omega^2)} = \frac{U^2}{2\pi}\frac{M_W}{M_p}\frac{(\frac{1}{4}\omega^4-\omega^2M_p^2)^{1/2}}{Q^2}\frac{\sigma(\omega)}{(\Delta^2-M_p^2)^2}, \tag{1}$$

where σ is the nucleon-nucleon cross section at energy ω, Q is the momentum of the incident proton, and U is the matrix element for the weak-interaction vertex, taken here as

$$4\pi U^2 = \frac{G^4}{4M_p^2}\,|(p_l+p_v)(p_\mu-p_\nu)|^2\int\frac{dq^2}{|(M_W-i\Gamma/2)^2+q^2|^2}, \tag{2}$$

where p_l, p_v, p_μ, and p_ν are the four-momenta of the incident proton, the virtual nucleon, the muon from the W decay and the neutrino. The W decay width is equal[5] to $G^2M_W^2/6\pi B$, where B is taken here[7] as $\frac{1}{4}$, and G^2 is the weak-interaction coupling constant given by $G^2M_p^2 = 10^{-5}M_W^2/\sqrt{2}$. The expression of Eq. (1) should be modified by the product of two form factors. From the hypothesis of conserved vector current we can expect that the form factor for the weak-interaction vertex (p, W, n) can be taken as nearly the same as the timelike isovector electromagnetic form factor for the nucleon at a momentum transfer $q^2 = M_W^2$. A second form factor, $\exp(-3t)$, is also used, where t is the absolute square of the minimum four-momentum transfer required to put the virtual baryon on the mass shell. This factor does not affect the cross sections very much. The matrix element of Eq. (2) represents an approximation where the spins of the baryons are suppressed by considering the baryons as scalar particles. In this approximation there is but one amplitude and one form factor which can be considered as an appropriate average over the several form factors required for a more complete description (which does not seem to be warranted at this time). Aside from this approximation, the formula of Eq. (1) represents an approximation which neglects all singularities in the amplitude as a function of the variable Δ^2 except the nucleon pole. Therefore the expression is not likely to be useful except where $(\Delta^2-M_p^2)^2$ is quite small. This is not the case for the results presented here where Δ^2 is typically of the order of $-M_p^2$. We can estimate the effect of the extrapolation by borrowing from the results of other baryon-exchange measurements and multiplying the expression for the differential cross section by a factor $\exp[B(s)(\Delta^2-M_p^2)]$, where s is the square of the center-of-mass energy and $t=-\Delta^2$ is the square of the four-momentum transfer. If we take $B=0.9\ln s$, we have a Regge form[8] for the factor, and both the variation of cross section with t and s and the magnitudes of the cross sections calculated in this way are consistent with cross sections measured for similar baryon-exchange reactions.[9] Certain other calculations of W production in nucleon-nucleon interactions[10] have resulted in very much larger cross sections —larger by factors of 10^4! —but it is not clear that such optimism is warranted.

Differential cross sections for the production of 25.1-GeV muons in the forward direction, calculated from these considerations (which may be much too pessimistic) as a function of the W mass, are presented in Fig. 1(c). For definiteness, the branching ratio B is taken as $\frac{1}{4}$. The cross sections must be multiplied further by the square of the form factor for the nucleon-W-nucleon vertex which we assume is approximately the same as the electromagnetic form factor. While the electromagnetic form factor of the nucleon is not well known in the timelike region,[11,12] experimental measurements[13,14] concerning the production of lepton pairs in proton-antiproton annihilation show that the square of the form factor is not much larger than 10^{-2} for $-4\ (\text{GeV}/c)^2 \geqslant q^2 \geqslant -7\ (\text{GeV}/c)^2$. For our purpose we can take $-q^2 = M_W^2$. Clearly if the form factor is this small our results cannot be considered as strong evidence that a W particle does not exist in the mass range accessible to this experiment. The cross section for the production of W's by nucleon-nucleon interactions could well be very much smaller than the cross section for production by neutrino-nucleon interactions.

It is useful, primarily as a matter of communication, to consider the resultant limits in terms of a total cross section for W production. Since this measurement, like previous measurements, concerns only differential cross sections over specific ranges of energies and angles, an estimate of the total cross section cannot be model independent. However, a useful estimate of a total cross section can be made by integrating Eq. (1), as modified by the Regge-pole extension, over the kinematic limits and comparing the total cross sections with the differential cross sections in the region which was measured. The experimental limits on the differential cross sections are then interpreted as limits on the total cross sections and these limits are plotted in Fig. 1(c). The experimental limits of $B\sigma \lesssim 6\times10^{-36}$ cm^2 are about 100 times smaller than the limits set previously.

The value of the cross section for "prompt" muons presented here corresponds to about 10^{-6} times the pion flux at the same energy and angle. The results of the Utah group[15] suggest that at very high energies, $E_p \gtrsim 3000$ GeV, the ratio of prompt muons to pions is about 2×10^{-2}. Our results then indicate that the anomaly required by the Utah results is very small or nonexistent at $E_p = 28$ GeV.

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[1]F. E. Low, Comments Nucl. Particle Phys. 2, 33 (1968).

[2]M. Gell-Mann, M. L. Goldberger, N. M. Kroll, and F. E. Low, Phys. Rev. 179, 1518 (1969).

[3]G. Bernardini et al., Nuovo Cimento 38, 608 (1965); R. Burns et al., Phys. Rev. Letters 15, 42 (1965).

[4]R. Burns et al., Phys. Rev. Letters 15, 830 (1965); R. C. Lamb et al., Phys. Rev. Letters 15, 800 (1965). See also R. Burns et al., Columbia University Nevis Laboratories Report No. NEVIS-153, 1966 (unpublished).

[5]Y. Yamaguchi, Nuovo Cimento 43A, 193 (1966).

[6]G. F. Chew and F. E. Low, Phys. Rev. 113, 1640 (1959).

[7]V. Namias and L. Wolfenstein, Nuovo Cimento 36, 542 (1965).

[8]R. Omnes and M. Froissart, Mandelstam Theory and Regge Poles (W. A. Benjamin, Inc., New York, 1965).

[9]J. V. Allaby et al., Phys. Letters 29B, 198 (1969), have studied the closely related reaction $p+p\rightarrow \mathrm{D}+\rho$.

[10]F. Chilton, Argonne National Laboratory Report No. ANL 7130, 1965 (unpublished), p. 254. See also F. Chilton, A. M. Saperstein, and E. Shrauner, Phys. Rev.

148, 1380 (1966).
[11]R. Wilson, Phys. Today 22, No. 1, 47 (1969).
[12]T. Massam and A. Zichichi, Nuovo Cimento 43A, 1137 (1966).
[13]M. Conversi et al., Nuovo Cimento 40A, 690 (1965).
[14]D. L. Hartill et al., California Institute of Technology Report No. CALT-68-175 (unpublished).
[15]H. E. Bergeson, J. W. Keuffel, M. O. Larson, G. W. Mason, and J. L. Osborne, Phys. Rev. Letters 21, 1089 (1968).

BARYON OCTET MASSES IN BROKEN SU(3) ⊗ SU(3) *

Yuk-Ming P. Lam and Yee Yen Lee†
The Enrico Fermi Institute, The University of Chicago, Chicago, Illinois 60637
(Received 11 July 1969)

We calculate the contribution to the baryon octet masses of the symmetry breaking term u_0+cu_8 by means of a phenomenological Lagrangian. Our result gives a theoretical justification of the conclusion of von Hippel and Kim.

The success of chiral SU(3) ⊗ SU(3) is based on Nambu's idea[1] that, in the limit of exact symmetry, the pseudoscalar octet has exactly zero masses. Gell-Mann's original idea[2] that this group is broken by a term in the Hamiltonian proportional to $(-u_0-cu_8)$ [where u_i, v_i, for $i=0, 1, \cdots, 8$, form a basis of the representation $(\underline{3}, \underline{3}^*)\oplus(\underline{3}^*, \underline{3})$ of the chiral SU(3) ⊗ SU(3) group, and c is a constant] was recently revised by Gell-Mann, Oakes, and Renner,[3] and the value $c=-1.25$ was suggested. This shows that SU(2) ⊗ SU(2) is a very nearly exact symmetry (and so the pion mass is nearly zero). By using the soft-pion theorem, coupled with a method of extrapolation to the mass shell, von Hippel and Kim[4] put these ideas to work in the domain of threshold amplitudes; and by fitting to experimental data, they obtained the conclusion that the expectation value of u_0 between the octet baryon states,

$$\mu_0=-\langle B|u_0|B\rangle,$$

is approximately 175 MeV. A recent private communication with von Hippel revealed that he has updated this value to about 200 MeV. As a result, the common mass of the baryon octet before the symmetry was broken was very close to (and slightly lower than) the actual nucleon mass, where the SU(3) ⊗ SU(3) symmetry is already broken. Thus, this result seems to suggest that breaking of SU(3) ⊗ SU(3) only gives the nucleon mass a very small positive increment. In this note, we are going to justify this result by employing the same ideas and a very simple and physically attractive assumption.

We will use the mathematical technique of the phenomenological Lagrangian developed by Callan, Coleman, Wess, and Zumino.[5] The linear subgroup used here is the usual SU(3). The system which we will now consider consists of eight pseudoscalar meson fields ξ_i (which are dimensionless for the moment; actually they are normalized by the factor $F_\pi=F_K=F_\eta$) and eight $\frac{1}{2}^+$ baryons B_i. The (anti-Hermitean) generators V_i, A_i $(i=1,\cdots,8)$ of SU(3) ⊗ SU(3) satisfy the commutation relations

$$[V_i,V_j]=[A_i,A_j]=f_{ijk}V_k,$$

$$[V_i,A_j]=f_{ijk}A_k.$$

For any octuple of fields ξ_i, and any element g of SU(3) ⊗ SU(3), we define the quantity ξ_i' and μ_i' by[6]

$$ge^{\xi\cdot A}=e^{\xi'\cdot A}e^{\mu'\cdot V}. \tag{1}$$

Further, we define

$$B_i'=(e^{\mu'\cdot T})_{ij}B_j, \tag{2}$$

where $(T_i)_{jk}=-f_{ijk}$ are the generators of the eight-dimensional representation of SU(3). The nonlinear transformation of the vector (ξ_i,B_j) under g is given in Ref. 5 as

$$g\colon\ (\xi_i,B_j)\to(\xi_i',B_j'). \tag{3}$$

Then we may interprete the ξ's and B's as the baryon and meson field operators, respectively.

The result of Ref. 5 will now be used to construct functions of ξ_i and B_i that transform linearly under SU(3) ⊗ SU(3). These functions and their transformation properties under SU(3)