in the ideogram may not belong to the resonance [see discussion following Eq. (7)], the finite width of the resonance suggested by Fig. 3 cannot be regarded as certain. However, an upper limit $\Gamma < 5$ MeV seems justified by the remaining curves in Fig. 3 which show (without normalization) the resolution function folded with resonance curves of the form $Q^{3/2}/[(Q-Q_\gamma)^2+(\Gamma/2)^2]$.

The small Γ of the resonance also argues against the presence of an allowed two-pion strong decay mode.[11] It therefore appears very probable that the resonance has $G=-1$ and hence, with $l=1$, $I=0$. The $I=0$, $J^{PG}=1^{--}$ quantum number assignment agrees completely with that proposed by Sakurai[11] for a vector boson he called φ and we would like to adopt this symbol for the resonance. The upper limit on Γ observed here agrees with the width calculated by Sakurai for the $K\bar{K}$ decay mode alone. It is possible, therefore, that the 3π decay mode does not play an important role in φ decay.

We wish to thank Professor E. M. MacMillan for the opportunity of carrying out experiments at the Lawrence Radiation Laboratory. The friendly cooperation of the entire hydrogen bubble chamber group and, in particular, the continued support of Professor Luis Alvarez, are gratefully acknowledged. We are indebted to Professor J. J. Sakurai for a most stimulating correspondence concerning the properties of the φ. Last, but not least, we wish to thank our scanners for their careful work.

*This work supported in part by the U. S. Atomic Energy Commission, Contract AT(11-1)-34.

[1]A. R. Erwin, G. A. Hoyer, R. H. March, W. D. Walker, and T. P. Wangler, Phys. Rev. Letters 9, 34 (1962).

[2]L. Bertanza et al., Phys. Rev. Letters 9, 180 (1962).

[3]G. Alexander, O. I. Dahl, L. Jacobs, G. R. Kalbfleisch, D. H. Miller, A. Rittenberg, J. Schwartz, and G. A. Smith, Phys. Rev. Letters 9, 460 (1962).

[4]A. Bigi, S. Brandt, R. Carrara, W. A. Cooper, A. de Marco, G. R. MacLeod, Ch. Peyrou, R. Sosnowski, and A. Wroblenski, Proceedings of the International Conference on High-Energy Nuclear Physics, Geneva, 1962 (CERN Scientific Information Service, Geneva, Switzerland, 1962) p. 247.

[5]M. Goldhaber, T. D. Lee, and C. N. Yang, Phys. Rev. 112, 1796 (1958).

[6]See Proceedings of the International Conference on High-Energy Nuclear Physics, Geneva, 1962 (CERN Scientific Information Service, Geneva, Switzerland, 1962) footnote p. 282 and discussion pp. 288-9.

[7]More recently 45% of the 2-prong-plus-V events have been measured completely. No additional ΛK^+K^- were found.

[8]S. B. Treiman, Phys. Rev. 128, 1342 (1962).

[9]The $2K_1^0$ event, the K^+K^- event located completely outside the resonant region in Fig. 1, and one K^+K^- event where the Λ decayed leptonically, were not used in this analysis.

[10]S. L. Glashow, Phys. Letters 2, 251 (1962).

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

[12]Using the value of $B=0.294\pm0.021$ of Chretien et al., as quoted by F. S. Crawford, Proceedings of the International Conference on High-Energy Nuclear Physics, Geneva, 1962 (CERN Scientific Information Service, Geneva, Switzerland, 1962) p. 836.

EXISTENCE AND PROPERTIES OF THE φ MESON*

P. L. Connolly, E. L. Hart, K. W. Lai, G. London,† G. C. Moneti,‡ R. R. Rau, N. P. Samios, I. O. Skillicorn, and S. S. Yamamoto
Brookhaven National Laboratory, Upton, New York

and

M. Goldberg, M. Gundzik, J. Leitner, and S. Lichtman
Syracuse University, Syracuse, New York
(Received 27 March 1963)

In a previous publication[1] we reported evidence for the existence of a resonance in the $K\bar{K}$ system (which we shall call the φ meson[2]) with a mass of ~1020 MeV and a width ≤20 MeV. The purpose of this Letter is to report additional data, the analysis of which confirms the existence of the resonance[3] and provides a conclusive determination of the mass, width, parity, spin, isospin, and branching ratios of this resonance. In particular we find $M=1019\pm1$ MeV, $\Gamma=1_{-1}^{+2}$ (with $\Gamma>0$), parity $(P)=-1$, spin $(J)=1$, isotopic spin $(I)=0$, and charge conjugation $(C)=-1$. The vector nature of the φ clearly establishes that it is not related to the mass enhancement in the K_1K_1 system observed by other groups.[4]

This experiment is part of a continuing study of the K^--p interaction[5] at 2.23 BeV/c. The data were collected in two exposures of the 20-

inch BNL hydrogen chamber at Brookhaven's AGS. Our study of the $K\bar{K}$ system is based upon the reactions

$$K^- + p \to \Lambda + K^0 + \bar{K}^0, \quad (1)$$

$$K^- + p \to \Lambda + K^+ + K^-. \quad (2)$$

We shall refer to (1) as the "neutral channel" and to (2) as the "charged channel." At present, the total analyzed data consist of channels (1) and (2) from the first exposure[6] and channel (1) from the second exposure; the numbers of events involved are summarized in Table I. A total of 36 events in the neutral channel and 22 events in the charged channel have been analyzed.

The general analysis procedure used to identify events on the basis of χ^2 fitting and ionization information is described in detail in a previous publication.[5] Background contamination and detection bias are negligible. Owing to the difference in neutral missing mass, channel (1) events are easily distinguished from the competing reactions, $K^- + p \to \Xi^0 + K^0$ and $\pi^- + p \to (\Lambda \text{ or } \Sigma^0) + K^0$ $(+\pi^0)$. Competition from $\pi^- + p \to \Lambda + K^0 + 2\pi^0$ is negligible due to the small pion contamination in the beam and the small phase space available for this reaction. This is further substantiated by the paucity of events of the type $\pi^- + p \to \Lambda + K^0 + \pi^+ + \pi^-$, only two such events occurring in the first run. The only significant background is due to the reaction $K^- + p \to \Sigma^0 + K^0 + \bar{K}^0$, which we estimate on the basis of missing mass studies and other information to be ~10%. Because of severe competition from other modes, candidates for channel (2) are used only if the Λ decays visibly. Due to the more frequent occurrence of the topologically similar reactions $K^- + p \to \Lambda + \pi^+ + \pi^-$ and $K^- + p \to \Lambda + \pi^+ + \pi^- + \pi^0$, it was necessary to measure all events consisting of a V and two charged prongs. For those cases which were kinematically ambiguous it was always possible to determine the $\Lambda K^+ K^-$ events due to the difference in predicted ionization for the K's and π's. We therefore believe the charged channel to be free from bias.

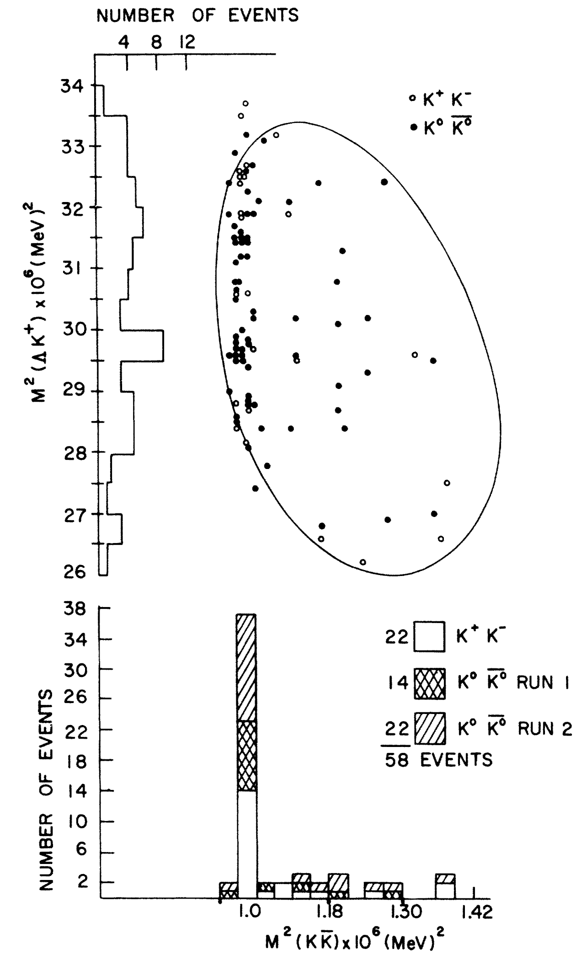

FIG. 1. Dalitz plot for the reaction $K^- + p \to \Lambda + K + \bar{K}$. The effective-mass distribution for $K\bar{K}$ and for ΛK^+ are projected on the abscissa and ordinate (see reference 7).

The Dalitz plot of the (squared) $K\bar{K}$ and ΛK[7] effective masses of 58 events from both the neutral and charged $K\bar{K}$ channels is shown in Fig. 1. The enhancement over the phase-space distribution in the region $M^2(K\bar{K}) = 1.04$ BeV^2 is ap-

Table I. Summary of events from both exposures.

	No. of events Channel (1)	No. of events Channel (2)	No. of events in peak Channel (1)		No. of events in peak Channel (2)	
			Obs.	Corrected	Obs.	Corrected
First exposure	14	22	9	19	14	23
Second exposure	22	Not analyzed	13	Not Useful	Not analyzed	

parent,[8] as is the lack of any significant irregularity in the $M^2(\Lambda K)$ distribution, indicating the absence of any appreciable ΛK-$K\bar{K}$ interference. A comparison of the observed φ peak with the K_1K_1 enhancement found by Alexander et al.[4] clearly indicates on the basis of widths alone that the two effects are different.

We have examined the enhancement region of Fig. 1 by plotting an ideogram of $M(K\bar{K})$ for events between 1000 and 1040 MeV. This distribution peaks at 1019 ± 1 MeV and has an observed width of ~10 MeV. We defer a discussion of the true width Γ since its determination is to some extent influenced by the spin quantum number assigned to the φ.

First, we consider the parity of the φ, or that which is equivalent for a $K\bar{K}$ system, the charge conjugation number, C. Determination of C rests upon the observation by Goldhaber et al.[9] that if the $K\bar{K}$ system has $C = +1$, it may decay into K_1K_1 or K_2K_2, while if it has $C = -1$, it may decay only into K_1K_2. Taking account of these correlations we may compute, for both $C = +1$ and $C = -1$ hypotheses, the expected rates of φ decay into the experimentally observable topological variations of final states of channel (1), which we label by their visible V's as follows: ΛK_1K_1, ΛK_1, and K_1K_1. The predicted[10] relative rates of ΛK_1K_1, ΛK_1, and K_1K_1 are given in Table II. If these are compared with the observed rates, also given in Table II, one sees that the $C = -1$ hypothesis is in excellent agreement with the data, while the $C = +1$ hypothesis is in disagreement with the data by 12 standard deviations; this is just a reflection of the fact that there are 23 events in the peak which are ΛK_1, and not one ΛK_1K_1 or K_1K_1. We conclude, therefore, that the φ has $C = P = -1$, or equivalently that its spin is odd, the most likely values being $J = 1$ or 3.

Information concerning the spin can be obtained from a consideration of the (relative) decay rate α_J, where

$$\alpha_J = \frac{\varphi \to K_1K_2}{\varphi \to K_1K_2 + K^+K^-}.$$

In the absence of a K^+K^0 mass difference and charge effects, the ratio α is clearly independent of J (in fact $\alpha = 0.5$). The spin dependence of α_J arises from the different angular momentum and Coulomb barriers appropriate to the (K_1K_2) and (K^+K^-) systems. Using an interaction radius[11] of $(2M_\pi)^{-1}$, a Coulomb correction of 4% for $J = 1$ and 3% for $J = 3$, and center-of-mass momenta of $P_\pm = 125$ MeV/c and $P_0 = 107$ MeV/c, we estimate $\alpha_{J=1} = 0.39$ and $\alpha_{J=3} = 0.26$. From the (first exposure) data of Table I, after correcting for neutral modes and fiducial region differences, we find $\alpha_{\text{expt}} = 0.45 \pm 0.10$. Comparing this with our theoretical estimates we see that the observed ratio of relative kaon decay modes is in good agreement with the $J = 1$ hypothesis and disagrees with that of $J = 3$ by ~2 standard deviations. In principle further information on the spin can be obtained from the shape of the φ peak. If the φ meson has a finite width, and if our experimental resolution is symmetric, then the observed shape of $M(K\bar{K})$ should exhibit an asymmetry depending on the spin J. The $M(K^+K^-)$ and $M(K_1{}^0K_2{}^0)$ distributions in the form of Gaussian ideograms as well as their respective resolution functions[12] are shown in Fig. 2. In both instances there appear similar asymmetries. Since the phase-space background is extremely small ($1\frac{1}{2}$ events) it is probable that the $M(K\bar{K})$ asymmetry[13] reflects the spin dependence of the φ decay. The experimental data was then fitted with both p- and d-wave modified Breit-Wigner formula including the experimental mass resolution. Both

Table II. Predicted and observed relative rates for different topological types of channel (1).

Topological Type of Channel (1)	Predicted Relative Rates $C = -1$ (K_1K_2)	$C = +1$ (K_1K_1) (K_2K_2)	Observed Relative Rates For Events in Peak
ΛK_1K_1	0	0.4	0 ± 0.04
ΛK_1	1	0.4	1 ± 0.2
K_1K_1	0	0.2	0 ± 0.04

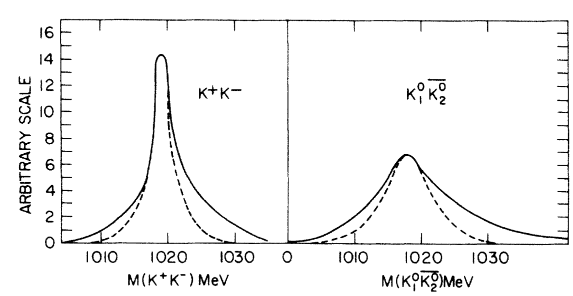

FIG. 2. The solid curve is the Gaussian ideogram of the $(K\bar{K})$ mass spectrum after subtraction of phase space. The dashed curve is the Gaussian ideogram of the $(K\bar{K})$ mass resolution function.

spin-1 and spin-3 cases fit the data for slightly different values of the true width Γ_T. Since the charged (K^+K^-) masses are considerably better determined ($\Gamma_{+-}{}^{\rm res} = 3 \pm 1$ MeV) than their neutral ($K_1{}^0\bar{K}_2{}^0$) counterpart ($\Gamma_{0\bar{0}}{}^{\rm res} = 8 \pm 2$ MeV), they constitute a more suitable sample from which to obtain Γ_T. Taking into account background and statistical uncertainties we find $\Gamma_T = 1_{-1}^{+2}$ MeV, and as argued above we believe $\Gamma_T > 0$.

Next, we consider the isotopic spin of the φ. The strongest evidence concerning isospin comes from a determination of the G-parity (G). Since we have established that the φ spin is odd, then $G = -(-1)^I$. If the G-parity of the φ were +1, the G-allowed 2π decay mode would predominate over the $K\bar{K}$ mode. From the ratio of phase space and barrier penetration factors (for $J = 1$) we find that $(Q \to 2\pi)/(Q \to K\bar{K}) \cong 10$ for an interaction radius $R = (1/2m_\pi)$ and increases to $\cong 20$ for $R = (1/2m_p)$. We have searched for a 2-pion decay mode by investigating the $M(\pi^+\pi^-)$ distribution from the reaction

$$K^- + p \to \Lambda + \pi^+ + \pi^-. \qquad (3)$$

The $\Lambda\pi^+\pi^-$ final state frequently results from the decay of a $Y_1{}^*$ intermediate state,[14] a circumstance which would complicate the search for $\varphi \to 2\pi$, therefore the $Y_1{}^*$ production events were removed on the basis of their $M(\Lambda\pi)$ values (taken as 1385 ± 40 MeV for present purposes).[15] The $M(\pi^+\pi^-)$ distribution of the remaining events is shown as the solid curve of Fig. 3. There is no evidence of enhancement at 1020 MeV which would indicate $\Lambda + \varphi$ production. We estimate that the 300-event sample of Fig. 3 (from the first exposure only) does not contain more than five $\varphi \to 2\pi$ events. From this, and the $K\bar{K}$ data of the first exposure (see Table I), taking into account corrections for unobservable modes,

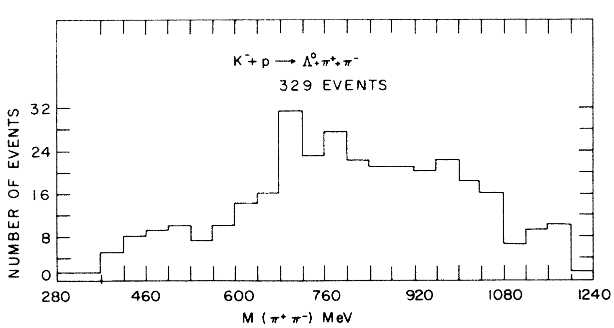

FIG. 3. The $M(\pi^+\pi^-)$ distribution from the reaction $K^- + p \to \Lambda + \pi^+ + \pi^-$ after removing $Y_1{}^*$ production events (see text).

we find an upper limit to the relative 2π rate of

$$\left(\frac{\varphi \to 2\pi}{\varphi \to K\bar{K}}\right) = \frac{5}{19 + 23} < 0.2.$$

Since the discrepancy between this upper limit and the predicted lower limit of this $G = +1$ decay is about 2 orders of magnitude, we conclude[16] that the φ has negative G-parity, which implies isotopic spin 0.

For a φ with negative G-parity and spin 1, the main competition to the $K\bar{K}$ decay mode is expected to come from[17] 3π decay, and in particular from the mode $\varphi \to \rho + \pi$. We have searched for the latter decay mode in the final state

$$\Lambda + \pi^- + \pi^+ + \pi^0. \qquad (4)$$

As discussed in an earlier publication,[5] only ~60% of the final states (4) arise from the nonresonant reaction $K^- + p \to \Lambda + \pi^- + \pi^+ + \pi^0$. The remainder of the $\Lambda + \pi^+ + \pi^- + \pi^0$ final states result from the decay of the following resonant intermediate states: (5) $Y_1{}^* + \pi + \pi$ or (6) $\Lambda + \omega$, (7) $\Lambda + \varphi$, (8) $\Lambda + \rho + \pi$. In order to avoid correlations in the 3π system due to $Y_1{}^*$ decay, the intermediate states (5), which may be recognized by means of a $\Lambda\pi$ effective mass[15] of 1385 ± 30, are removed from the sample of $\Lambda + \pi^+ + \pi^- + \pi^0$ final states. The 2π mass spectrum is searched for events with a ρ mass, taken[15] to be 750 ± 75 MeV. For events satisfying these criteria, their 3π effective mass spectrum, shown as the solid curve of Fig. 4, is examined for evidence of a

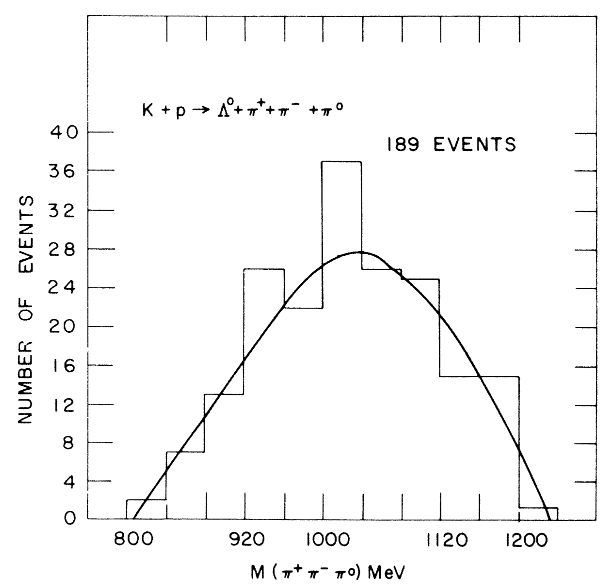

FIG. 4. The $M(\pi^+\pi^-\pi^0)$ distribution from the reaction $K^- + p \to \Lambda + \pi^+ + \pi^- + \pi^0$ after removing $Y_1{}^*$ production events (see text).

peak at the φ mass. There is a deviation at $M(3\pi) = 1020$ MeV of about 1.5 standard deviations above background and of width consistent with the experimental resolution at this mass. The sample of Fig. 4 representing all available data from the first exposure contains ~10 $\varphi \to \rho + \pi$ events. From this and the relevant $K\bar{K}$ data (see Table I) we find, correcting for neutral modes,

$$\beta = \frac{\varphi \to \rho + \pi}{\varphi \to K + \bar{K}} \approx 0.35 \pm 0.2.$$

One can estimate β_J either from the ratio of phase space, barrier penetration, spin, and isospin factors which give $\beta_{J=1} \approx 4$ for an interaction radius of $(2m_\pi)^{-1}$ or from a dynamical approach as done by Sakurai[2] giving $\beta_{J=1} \approx 3$. The observed rate is lower than these predicted values by one order of magnitude; however the above estimates are uncertain[18] by at least this amount so that this discrepancy need not be disconcerting.

It should be noted that the φ, being a 1^{--} meson, may be accommodated within a number of theories of elementary particles. In the unitary symmetry model of Gell-Mann,[19] the φ could be the heretofore absent (singlet) partner of the vector meson octet. It has been noted that the pseudoscalar meson octet and baryon supermultiplets satisfy the generalized mass formula[19,20] to a high accuracy. However, the same mass formula applied to the vector meson octet predicts an isosinglet mass of 930 MeV, which is different from the observed ω mass of 780 MeV. This discrepancy might be explained by the mixing of the ω and φ,[2] a possibility which arises since they have the same quantum numbers. Within the framework of Sakurai's "vector theory of strong interactions"[21] the φ may play the role of the vector meson B_Y coupled to the hypercharge current. Finally, with respect to the Chew-Frautschi conjecture,[22] the φ presumably starts a new trajectory, as do the other vector mesons.

We would like to acknowledge the invaluable assistance of the AGS staff, the BNL 20-inch crew, and many technical assistants. Two of us (J. L. and N. P. S.) are indebted to Professor J. Sakurai for stimulating conversations and correspondence.

---

*Research carried out under the auspices of the U. S. Atomic Energy Commission.

†Graduate student on leave from University of Rochester, Rochester, New York.

‡Presently at the Istituto Nazionale di Fisica Nucleare, Rome, Italy and The University of Roma, Rome, Italy.

[1]L. Bertanza et al., Phys. Rev. Letters 9, 180 (1962).

[2]This was suggested by J. J. Sakurai, Phys. Rev. Letters 9, 472 (1962).

[3]The existence of this resonance has also been confirmed by P. Schlein, W. E. Slater, L. T. Smith, D. H. Stork, and H. K. Ticho, Phys. Rev. Letters 10, 368 (1963).

[4]A. R. Erwin et al., Phys. Rev. Letters 9, 34 (1962); G. Alexander et al., Phys. Rev. Letters 9, 460 (1962).

[5]L. Bertanza et al., Proceedings of the International Conference on High-Energy Nuclear Physics, Geneva, 1962 (CERN Scientific Information Service, Geneva, Switzerland, 1962), pp. 279-284.

[6]The data published in reference 1 consisted of a partial sample at 2.23 BeV/c from the first exposure along with 8 events at 2.50 BeV/c.

[7]Since the K^0 cannot be distinguished from the $\bar{K}^0$, both the ΛK^0 and $\Lambda\bar{K}^0$ masses are plotted in the Dalitz plot. However, each one of these points is counted only as 1/2 event in the $M^2(\Lambda K)$ projection, so that it is properly normalized.

[8]As determined by a χ^2 test, the probability that the observed $M^2(K\bar{K})$ distribution is due to phase space production is less than 10^{-6}.

[9]M. Goldhaber, T. D. Lee, and C. N. Yang, Phys. Rev. 112, 1796 (1958).

[10]In determining these rates and all other K_1^0 decay rates we have taken $\Gamma(K_1^0 \to \pi^0 + \pi^0)/\Gamma(K_1^0 \to \text{total}) = 1/3$. See Proceedings of the International Conference on High-Energy Nuclear Physics, Geneva, 1962 (CERN Scientific Information Service, Geneva, Switzerland, 1962), p. 836.

[11]The choice $M = 2M_\pi$ is clearly open to question. It should be emphasized however that the predicted rates are not sensitive to the choice of M so long as $M \geq 2M_\pi$. The values of α_J for $M = 2M_K$ are $\alpha_{J=1} = 0.38$, $\alpha_{J=3} = 0.26$.

[12]A study of the shape of our mass resolution was carried out by measuring the $M(\pi^- p)$ distribution from Λ^0 decay, which is known to have 0 width and a Q value similar to φ decay. The observed $M(\pi^- p)$ distribution was indeed symmetric, being characterized by $M_\Lambda = 1116 \pm 0.5$ MeV.

[13]The $\Lambda^0 K^+ K^-$ sample is completely free from contamination, in particular from $\Sigma^0 K^+ K^-$. Although $\Sigma^0 K^0 \bar{K}^0$ contamination is present in the neutral sample, the similarity in the asymmetry of both distributions allows us to conclude that the contamination does not appreciably contribute to the observed asymmetry.

[14]L. Bertanza et al., Phys. Rev. Letters 10, 176 (1963).

[15]The data were studied using several values of the resonance width and no significant difference resulted.

[16]Additional direct evidence for $I = 0$ which is of an entirely preliminary nature comes from the absence of a φ-type enhancement in the $M^2(K\bar{K})$ distribution of

16 $I=1$ combinations, K^0K^- and $\bar{K}^0K^+$ produced in the reactions $K^-+p\to\Sigma^-+K^++\bar{K}^0$ and $K^-+p\to\Sigma^++K^-+K^0$. Further, if one assumes $I=1$, the triangular inequality relating these reactions to their neutral counterparts $K^-+p\to\Sigma^0+K^0+\bar{K}^0$ and $\Sigma^0+K^++K^-$, $[\sigma(\Sigma^+)]^{1/2}+[\sigma(\Sigma^-)]^{1/2} \geqslant 2[\sigma(\Sigma^0)]^{1/2}$, is violated to the extent $(3\pm3)^{1/2}+(0\pm1)^{1/2} \geqslant 2(22\pm5)^{1/2}$.

[17]We estimate, for example, that $\varphi\to2\pi$ via an electromagnetic transition is $\sim2\times10^{-3}$ less frequent than $\varphi\to K\bar{K}$. The 3π rate is dominated by $\varphi\to\rho+\pi$ because only two-body phase space is involved.

[18]Due to these uncertainties the ratio β provides essentially no new information on the φ spin.

[19]M. Gell-Mann, Phys. Rev. 125, 1067 (1962); California Institute of Technology Report CTSL-20, 1961 (unpublished). For appropriate remarks, also see reference 2.

[20]S. Okubo, Progr. Theoret. Phys. 27, 949 (1962).

[21]J. J. Sakurai, Ann. Phys. 11, 1 (1960); Phys. Rev. Letters 7, 335 (1961).

[22]G. F. Chew and S. C. Frautschi, Phys. Rev. Letters 8, 41 (1962).

7- TO 20-BeV/c π^-+p AND $p+p$ ELASTIC SCATTERING AND REGGE POLE PREDICTIONS*

K. J. Foley, S. J. Lindenbaum, W. A. Love, S. Ozaki, J. J. Russell, and L. C. L. Yuan
Brookhaven National Laboratory, Upton, New York
(Received 13 March 1963)

This Letter reports measurements of the elastic differential cross section from 7 to 20 BeV/c incident momentum for $p+p$ and 7 to 17 BeV/c for π^-+p over the t range 0.2 to 1.0 $(\text{BeV}/c)^2$, where t is the negative square of the Lorentz-invariant four-momentum transfer. This experiment is part of a program to study basic strong interactions in the energy range available at the Brookhaven AGS, i.e., ~10-20 BeV. These measurements are of great current interest due to the striking predictions made by the Regge pole theory and allow a critical evaluation of the theory. If the energy is sufficiently high that the vacuum or Pomeranchuk Regge trajectory dominates, one would expect as predicted by Chew and Frautschi[1] and others[2] that for any incident particle

$$\frac{d\sigma}{dt}=\left[\frac{d\sigma}{dt}\right]_{\text{opt}}F(t)\left[\frac{s}{s_0}\right]^{2\alpha_p(t)-2}, \qquad (1)$$

where $[d\sigma/dt]_{\text{opt}}$ is the minimum value of $d\sigma/dt$ at $t=0$ predicted from the optical theorem, s is the Lorentz-invariant square of the total center-of-mass energy, and s_0 is usually taken to be $2m_p^2$. This prediction obviously gives a shrinkage of $d\sigma/dt$ (logarithmic with s) corresponding at low t in a semiclassical way to a growth of the radius of interaction. Previous measurements[3] were of insufficient accuracy to establish such behavior above 10 BeV/c. The present $p+p$ scattering results do show a shrinkage of this type consistent with the Regge pole prediction but the π^-+p scattering shows no shrinkage, thus contradicting the assumption of dominance of the strong interactions by a single vacuum pole. Our results are also inconsistent with the predictions of the three-pole model of Hadjioannou et al.[4] and Drell,[5] which was developed to explain the total cross-section data – which are inconsistent with single-pole prediction. In the three-pole model F in Eq. (1) is a relatively weak function of s as well as a function of t but shrinkage of $d\sigma/dt$ is still predicted – with a modified $\alpha_p(t)$ which slightly overestimates shrinkage effects for $p+p$. Therefore, we will analyze as though the vacuum pole alone were important and then relate our results to the three-pole model.

Figure 1 shows the experimental arrangement. A $4\frac{1}{2}°$ secondary beam from the Brookhaven AGS was momentum analyzed and focussed at scintillator S_3, a circular counter 2 in. in diameter. This beam had a measured angular divergence of ±1.5 mrad and a momentum resolution of $\pm1\frac{1}{2}\%$ with the mean momentum known to better than 0.3%. The desired particle was selected by the scintillator telescope $S_1S_2S_3$ and a high-resolution differential gas Cherenkov counter C previously described.[6] The liquid hydrogen target was 4 in. in diameter by 20 in. long. The scattered particle was detected by the scintillation counter hodoscope, H_s, consisting of 12 vertical counters (2 in. wide by 12 in. high) and 12 horizontal counters (1 in. high by 24 in. long), defining 144 equivalent intersectional counter areas which covered the t range 0.2 to beyond 1.0 $(\text{BeV}/c)^2$. The recoil proton from the target was detected by two hodoscopes, the target screen, H_t, 12 vertical 2-in. wide counters alongside the target, and the recoil screen, H_r, 22 vertical and 22 horizontal counters all $2\frac{1}{2}$ in. wide by 60 in. long defining 484 equiva-