and the radiation carries off the energy

$$E=(2\omega+3)\pi^2\nu^2c^3\tau A^2/2G_0.$$

The magnitude of the spin-0 radiative component of the Riemann tensor is given by

$$R_0=(2A\pi^2\nu^2/rc^2)\sin 2\pi\nu u.$$

Morganstern and Chiu[12] give approximate values of τ and ν for the two reasonable limiting masses of a neutron star. For the upper limit on the mass, $\tau=6.3\times10^{-3}$ sec and $\nu=10^3$ cps, which leads to

$$R_0\approx10^{-10}/r\ \mathrm{cm}^{-1}.$$

For the lower mass limit, $\tau=83$ sec and $\nu=10^2$ cps, which gives

$$R_0\approx10^{-13}/r\ \mathrm{cm}^{-1}.$$

The thermal noise level of Weber's apparatus corresponds to

$$R_0=10^{-33}\ \mathrm{cm}^{-2}.$$

His instrumentation is sensitive to radiation above this level. Consequently, if the Brans-Dicke theory and present models for neutron stars are correct, neutron star events with favorable parameters which occur in our galaxy diameter $\approx10^{23}$ cm) would be in the detectable range.

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EVIDENCE FOR THE EXISTENCE OF TWO $Y_1^*(1660)$ RESONANCES†

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The production angular distribution of the reaction $K^-p\rightarrow Y_1^{*+}(1660)\pi^-$ around 2.6 GeV/c, measured by using the $(\Sigma\pi)^+$ and $(\Sigma\pi\pi)^+$ decay modes, is interpreted as evidence for two distinct $Y_1^*(1660)$ resonances.

The production properties of the $Y_1^*(1660)$ or $\Sigma(1660)$ discussed here were studied in the reactions

$$K^-p\rightarrow\Sigma^+\pi^+\pi^-\pi^-, \quad (1)$$

$$\rightarrow\Sigma^-\pi^+\pi^+\pi^-, \quad (2)$$

$$\rightarrow\Sigma^0\pi^+\pi^-, \quad (3)$$

$$\rightarrow\Sigma^+\pi^0\pi^-. \quad (4)$$

The data were obtained from an exposure of the Berkeley 72-in. hydrogen bubble chamber to a K^- beam from the Bevatron at momenta of 2.58, 2.61, and 2.70 GeV/c. The total K^- path-length equivalent for these momenta is 12.8 events/μb. The events in Reactions (1), (2), and (4) have been weighted to correct for biases in detecting short-lived and small-angle decay Σ's. The Σ^0 events in our sample have been weighted to correct for undetected short-lived Λ^0's and for Λ^0's that decayed outside our fiducial volume.[1] The separation of the $\Sigma^0\pi^+\pi^-$ final-state events from $\Lambda^0\pi^+\pi^-$ and $\Lambda^0\pi^+\pi^-\pi^0$ final states has been described by Siegel.[2]

From Reactions (1)-(4), we have analyzed the $\Sigma(1660)$ production in a quasi-two-body reaction of the type

$$K^-p\rightarrow X^+\pi^-, \quad (5)$$

where X^+ is the $(\Sigma\pi\pi)$ or $(\Sigma\pi)$ particle combination with an overall charge of +1. The production angle, θ^*, is the angle of the X^+ system with respect to the incident proton in the overall c.m.

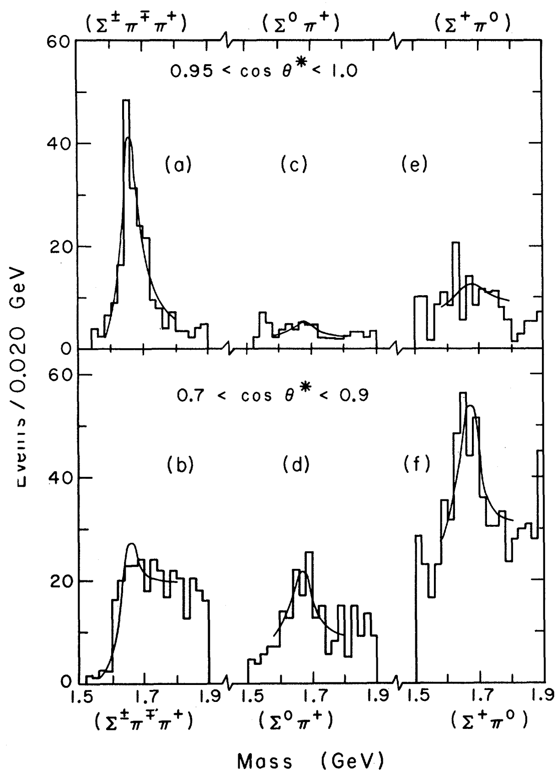

FIG. 1. Mass plots of the $\Sigma\pi\pi$ and $\Sigma\pi$ systems for various production $\cos\theta^*$ intervals. The events in the $(\Sigma^0\pi^+)$ spectra have not been weighted to correct for the unseen neutral decay of the Λ in the Σ^0 decay. The curves shown are the results from the fit described in the text.

system of Reaction (5).

Figures 1(a) and 1(b) show the invariant-mass distributions of the $(\Sigma\pi\pi)^+$ particle combination for those events of Reactions (1) and (2) with $0.95 < \cos\theta^* < 1.0$ (interval I) and $0.7 < \cos\theta^* < 0.9$ (interval III), respectively.[3,4] Figures 1(c)-1(f) show, respectively, the invariant-mass plots of the $\Sigma^0\pi^+$ system for Reaction (3) and the $\Sigma^+\pi^0$ system from Reaction (4), for the same intervals of $\cos\theta^*$ as for (a) and (b). Pronounced enhancements around a mass of 1660 MeV are seen in Figs. 1(a), 1(d), and 1(f) [i.e., for the $(\Sigma\pi\pi)^+$ system in interval I and for $(\Sigma^{0,+}\pi^{+,0})$ in interval III]. The contribution from the $\Sigma(1660)$ resonance is much less evident in Figs. 1(b), 1(c), and 1(e) [i.e., for the $(\Sigma\pi\pi)^+$ mode in interval III and the $(\Sigma^{0,+}\pi^{+,0})$ modes in interval I]. Thus the $\Sigma(1660)$ production is apparently more peripheral in the $\Sigma\pi\pi$ channel than in the $\Sigma\pi$ channel, or, in other words, the relative branching ratio $\Sigma\pi\pi/\Sigma\pi$ seems to depend upon the production angle of the resonance.

Quantitative results have been obtained by fitting the X^+ invariant-mass distributions for various intervals in $\cos\theta^*$ to a function of the form

$$p = (\text{phase space})\{a + b[\text{Breit-Wigner form for the } \Sigma(1660)]\}, \quad (6)$$

where the width of the Breit-Wigner term was considered as energy independent. Kinematical effects may cause shifts in the peak of the $\Sigma(1660)$ mass distributions; therefore we have determined the mass, width, and amount for each final state separately, using in each case a sample of events with $\cos\theta^* \geq 0.5$.

The masses and widths determined in this way were then fixed and used in subsequent fits to smaller $\cos\theta^*$ intervals. All fits were made in the mass range of 1580 to 1800 MeV. The fits with fixed mass and width were made for the $\cos\theta^*$ intervals listed in Table I and the curves resulting from these fits are shown in Fig. 1. From the fits we have determined the differential cross sections, in μb/sr, corresponding to the fraction of events due to the Breit-Wigner term. These cross sections are listed in Table I.

If these cross sections are due to the produc-

Table I. Results of fit to $\Sigma(1660)$ production in $\Sigma\pi\pi$ and $\Sigma\pi$ modes.

Mode	Amount of $\Sigma(1660)$ in interval (μb/sr) Interval I $0.95<\cos\theta^*<1.0$	Interval II $0.9<\cos\theta^*<0.95$	Interval III $0.7<\cos\theta^*<0.9$	Resonance parameters used in fit Mass (MeV)	Width (MeV)
$\Sigma^\pm\pi^\mp\pi^+$	57.0 ± 4.1	21.1 ± 3.8	8.1 ± 1.4	1651	70
$\Sigma^0\pi^+$	7.5 ± 4.6[a]	13.5 ± 5.5[a]	8.9 ± 2.5[a]	1667	80
$\Sigma^+\pi^0$	6.0 ± 5.5	6.4 ± 4.4	11.1 ± 2.7	1667[b]	80[b]

[a]Includes correction for unseen neutral decay of the Λ^0.
[b]Values taken from fit of $\Sigma^0\pi^+$ mass spectrum.

tion of a single $\Sigma(1660)$ resonance, then the results for the $\Sigma\pi\pi$ and $\Sigma\pi$ modes confirm the surprising and striking feature mentioned above that the $\Sigma(1660)$ relative branching ratio, $\Sigma\pi\pi/\Sigma\pi$, varies significantly with production angle. However, the $(\Sigma^0\pi^+)/(\Sigma^+\pi^0)$ relative branching ratio is consistent with unity, as expected, in all $\cos\theta^*$ intervals.

In Fig. 2, the measurements from each of the two $\cos\theta^*$ intervals I and III are represented by a point whose abscissa is our value of $d\sigma/d\Omega$ for the $\Sigma(1660)$ resonance in the $\Sigma\pi$ mode as obtained from Reaction (3) only,[5] and whose ordinate is $d\sigma/d\Omega$ for the resonance in the $\Sigma^\pm\pi^\mp\pi^+$ mode. On such a plot the errors are uncorrelated and approximately Gaussian. A one-standard-deviation ellipse surrounds each of the two points. The relative branching ratio $(\Sigma^\pm\pi^\mp\pi^+)/(\Sigma\pi)^+$ is the slope of the line from the origin to the plotted point.

For our results in regions I and III to be measurements of the same branching ratio would require a statistical accident equivalent to more than a three-standard-deviation fluctuation. For comparison, we also show in Fig. 2 the line for this branching ratio determined from the formation experiment of the CERN-Heidelberg-Saclay (CHS) groups.[6] Although our result in interval III is consistent with the CHS value, our result in interval I is not.

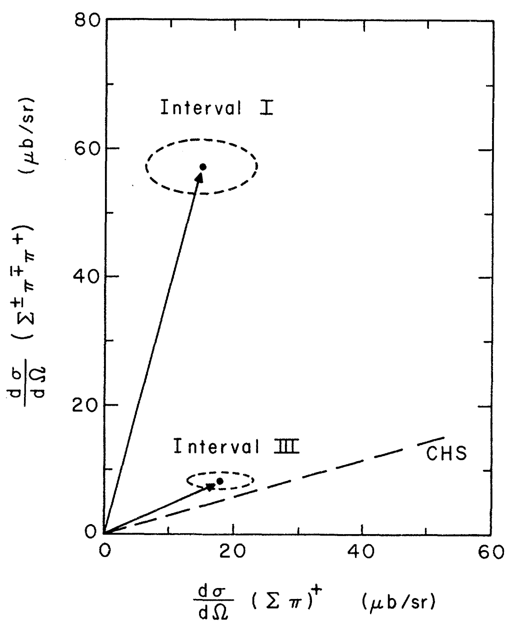

FIG. 2. Fitted amount of $\Sigma(1660)$ production in the $(\Sigma^\pm\pi^\mp\pi^+)$ mode versus that in the $(\Sigma\pi)^+$ mode, for two production $\cos\theta^*$ intervals (I,III) defined in the text and in Table I. The (dashed) ellipse around each of the two plotted points represents a one-standard-deviation error limit on the cross sections. The slope of the solid straight line from the origin to each of the two points is equal to the relative branching ratio $(\Sigma^\pm\pi^\mp\pi^+)/(\Sigma\pi)^+$, in the respective $\cos\theta^*$ interval. The slope of the dashed straight line from the origin is equal to the branching ratio result from the CHS formation experiment (Ref. 6).

The variable branching ratio can be explained by the presence of two resonances—one produced at very low momentum transfers (decaying primarily to $\Sigma\pi\pi$) and a second resonance (decaying primarily to $\Sigma\pi$) also produced peripherally but at higher momentum transfers. The CHS data[6] would also contain both these resonances, but probably mostly the latter, judging from their branching ratio in Fig. 2.

We have also explored the possibility that the variation of our measured branching ratio could result from an interference effect between the background[7] and the $\Sigma(1660)$ signal. We found this explanation quantitatively possible; however, it would require the following conditions: (a) A large fraction (say, 30 %) of the background would have to have the same spin, parity, and spin orientation as the $\Sigma(1660)$; (b) the interference would have to be nearly the maximum possible in both $\cos\theta^*$ intervals for both the $\Sigma\pi\pi$ and $\Sigma\pi$ modes; and (c) the relative phase between the resonance and background would have to change by more than 150 deg in going from interval I to III for both the $\Sigma\pi\pi$ and $\Sigma\pi$ modes. This explanation, involving all these various conditions, seems very unlikely to us. We therefore conclude that the most probable hypothesis is the existence of two hyperon resonances (with isospin 1) contributing to our mass enhancements in the 1660-MeV region.

This hypothesis could also account for some of the inconsistencies among the measured branching ratios of the $\Sigma(1660)$ in other production experiments[8,9]—a possibility already suggested by Primer et al.,[9] who speculated that there might be another resonance in the 1660-MeV region in addition to the $\Sigma(1660)$ and $\Sigma(1690)$. However, with regard to the $\Sigma(1690)$ reported seen in the $\Lambda\pi$ mode,[9] we have studied the $\Lambda\pi^+$ mass spectrum (not shown here) in the reaction $K^-p\to\Lambda\pi^+\pi^-$, and we find an enhancement in the 1660-MeV mass region with a relative branching ratio $\Lambda\pi^+/\Sigma^\pm\pi^\mp\pi^+=0.4\pm0.13$, in $\cos\theta^*$ interval I. This ratio disagrees significantly with the results quoted[9] for the $\Sigma(1690)$.

The two-$\Sigma(1660)$ hypothesis, in addition to explaining the significant branching-ratio variation with production angle in our data and being a possible explanation of the branching-ratio discrepancies in other production experiments, could also account for the inconsistencies between our results and those of the CHS formation experiment[6]—such as the inconsistency within the $\Sigma\pi\pi$ mode regarding the relative branching ratio of $\Sigma(1660) \rightarrow \Lambda(1405)\pi/[(\Sigma\pi)_{I=1}\pi]$.[10,11]

With regard to the spin and parity of these two resonances, the analysis of Ref. 4, using the entire data from the same bubble-chamber exposure used in this work, gives a spin and parity of $\frac{3}{2}^-$ for the $\Sigma\pi\pi$ mode. Furthermore, in the analysis of the $\Sigma^0\pi^+$ mode in another production experiment, Button-Shafer concludes[12] that a spin and parity of $\frac{3}{2}^-$ is also favored for this latter mode. Finally, the results of the CHS formation experiment also favor $\frac{3}{2}^-$ for the $\Sigma\pi$ mode of the $\Sigma(1660)$. The results, therefore, from these production and formation experiments indicate that the two resonances would have the same spin and parity, namely, $\frac{3}{2}^-$.

Two such resonances of the same isospin, spin, and parity could have their masses and widths quite different from each other and still interfere strongly with each other, so long as their Breit-Wigner shapes are overlapping. Therefore, the masses and widths of the two $\Sigma(1660)$'s listed in Table I, resulting from our simple fit of the $\Sigma\pi\pi$ and $\Sigma\pi$ mass spectra, would not necessarily represent the true and unperturbed values of these resonances. In fact, any enhancement of spin and parity $\frac{3}{2}^-$ seen in the $\Sigma(1660)$ region would in principle contain a linear combination of two basic resonances. For example, this would be true of the objects which we observed to decay into the $\Sigma\pi\pi$ and $\Sigma\pi$ final states; also the $\Sigma(1690)$ could be a linear combination of these two basic resonances if its spin and parity is $\frac{3}{2}^-$.

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[1]The average weight of the Σ^+ events in Reactions (1) and (4) is 1.40; that of the Σ^- events in Reaction (2) and the Σ^0 events in Reaction (3) is 1.14 and 1.10, respectively. The Σ^0 weights do not include the correction for the unseen neutral decay mode of the Λ. However, the results of the fit in Table I do include this latter correction.

[2]D. M. Siegel, thesis, University of California Radiation Laboratory Report No. UCRL-18041, 1967 (unpublished).

[3]We have combined the data of Reactions (1) and (2), since our investigation shows that the $\Sigma(1660)$ production characteristics are the same and the background is small, in both reactions. The $\Sigma(1660)$ relative branching ratio, $(\Sigma^+\pi^+\pi^-)/(\Sigma^-\pi^+\pi^+)$, in our data is about 1.8 and does not appear to change with production angle. The deviation from unity of this branching ratio is explained in P. Eberhard, M. Pripstein, F. T. Shively, U. E. Kruse, and W. P. Swanson, Phys. Rev. 163, 1446 (1967). This phenomenon does not affect the analysis of the work presented here.

[4]Eberhard, Pripstein, Shively, Kruse, and Swanson, Ref. 3.

[5]Because the peak-to-background ratio for the $\Sigma^0\pi^+$ events is considerably better than that for the $\Sigma^+\pi^0$ events (2.3 for $\Sigma^0\pi^+$ compared with 1.24 for $\Sigma^+\pi^0$ in $\cos\theta^*$ interval III), we use 2 times the $\Sigma^0\pi^+$ mode as our measurement of the total $\Sigma\pi$ mode of production of $\Sigma(1660)$. This procedure reduces the uncertainties due to possible interference with background.

[6]R. Armenteros et al., "Study of the Reaction $K^-N \rightarrow \Sigma\pi\pi$ between 600 and 1200 MeV/c" (to be published); R. Armenteros et al., in Proceedings of the Fourteenth International Conference on High Energy Physics, Vienna, 28 August-5 September 1968 (CERN Scientific Information Service, Geneva, Switzerland, 1968), paper No. 629. A summary of most of the results from the CERN-Heidelberg-Saclay formation experiment is given by R. D. Tripp, in Proceedings of the Fourteenth International Conference on High Energy Physics, Vienna, 28 August-5 September 1968 (CERN Scientific Information Service, Geneva, Switzerland, 1968), p. 173.

[7]The background was considered to be energy independent, with its amplitude and phase allowed to vary within a given production $\cos\theta^*$ interval.

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[9]M. Primer et al., Phys. Rev. Letters 20, 610 (1968); D. C. Colley et al., Phys. Letters 24B, 489 (1967); M. Derrick et al., Phys. Rev. Letters 18, 266 (1967).

[10]In our production experiment, the $\Sigma(1660)$ decay into the $\Sigma\pi\pi$ system is dominated by the $[\Lambda(1405)\pi]$ decay mode, as shown in Ref. 4 and in P. Eberhard, F. T. Shively, R. R. Ross, D. M. Siegel, J. R. Ficenec, R. I. Hulsizer, D. W. Mortara, M. Pripstein, and W. P. Swanson, Phys. Rev. Letters 14, 466 (1965), with the presence of a very small amount of the $[(\Sigma\pi)_{I=1}{}^0+\pi]$ mode (Ref. 4). In contrast to this, the CHS formation experiment (Ref. 6) yields an upper limit of 0.12 for the relative branching ratio $\Lambda(1405)\pi/\Sigma\pi$ and a measurement of 0.28 for $[(\Sigma\pi)_{I=1}{}^0+\pi]/\Sigma\pi$.

[11]Eberhard et al., Ref. 10.

[12]Janice Button-Shafer, Phys. Rev. Letters 21, 1123 (1968).