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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-inch 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^- pathlength 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 in Ref. 2.

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

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

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. system of reaction (5).

Figure 1 (a, b) shows 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] Figure 1 (c, d) and (e, f) show respectively the invariant-mass plots of the $\Sigma^0\pi^+$ system from reaction (3) and the $\Sigma^+\pi^0$ system from reaction (4), for the same intervals of $\cos\theta^*$ as for (a, b). Pronounced enhancements around a mass of 1660 MeV are seen in Fig. 1 (a, d, and f) [i.e., for the $(\Sigma\pi\pi)^+$ system in interval I and for $(\Sigma^+\pi^0)$ in interval III]. The contribution from the $\Sigma(1660)$ resonance is much less evident in Fig. 1 (b, c, and e) [i.e., for the $(\Sigma\pi\pi)^+$ mode in interval III and the $(\Sigma^+\pi^0)$ 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 distribution for various intervals in $\cos\theta^*$ to a function of the form

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

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 production 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.

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 isotopic spin 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 $K^-p \rightarrow \Lambda\pi^+\pi^-$, and we find an enhancement in the 1660-MeV mass region

with a relative branching ratio $\Lambda\pi^+/\Sigma^\pm\pi^\mp\pi^+ = 0.4 \pm 0.13$, 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-parity of $3/2^-$ 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-parity of $3/2^-$ is also favored for this latter mode. Finally, the results of the CHS formation experiment also favor $3/2^-$ 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-parity, namely, $3/2^-$.

Two such resonances of the same I-spin, 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 unperturbed values for these resonances. In fact, any enhancement of spin-parity $3/2^-$ 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-parity is $3/2^-$.

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FOOTNOTES AND REFERENCES

†Work done under auspices of the U. S. Atomic Energy Commission.

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), UCRL-18041, Dec. 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 Ref. 4. This phenomenon does not affect the analysis of the work presented here.

4. P. Eberhard, M. Pripstein, F. T. Shively, U. E. Kruse, and W. P. Swanson, Phys. Rev. 163, 1446 (1967).

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 (preprint, Oct. 1968), submitted to Nucl. Phys.;
R. Armenteros et al., Paper No. 629, XIVth International Conference

on High-Energy Physics, Vienna, 28 August - 5 September, 1968. A summary of most of the results from the CERN-Heidelberg-Saclay formation experiment is given by R. D. Tripp, rapporteur's talk, in Proceedings of the XIVth International Conference on High-Energy Physics, Vienna, 28 August - 5 September, 1968 (CERN, Scientific Information Service, Geneva 23, Switzerland), 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.

8. D. O. Huwe (thesis), UCRL-11291, July 1964 (unpublished). G. London et al., Phys. Rev. 143, 1034 (1966); Birmingham-Glasgow-London (I.C.)-Oxford-Rutherford Collaboration, Phys. Rev. 152, 1148 (1966); D. J. Crennell et al., Phys. Rev. Letters 21, 648 (1968). Further references may be found in A. H. Rosenfeld et al., Rev. Mod. Phys. 40, 77 (1968).

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 Refs. 4 and 11, with the presence of a very small amount of the $[(\Sigma\pi)^0_{I=1} + \pi]$ 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 $[(\Sigma\pi)^0_{I=1} + \pi]/\Sigma\pi$.

11. 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).

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

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)			Resonance parameters used in fit	
	Interval I $0.95<\cos\theta^*<1.0$	Interval II $0.9<\cos\theta^*<0.95$	Interval III $0.7<\cos\theta^*<0.9$	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.

FIGURE CAPTIONS

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.

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).

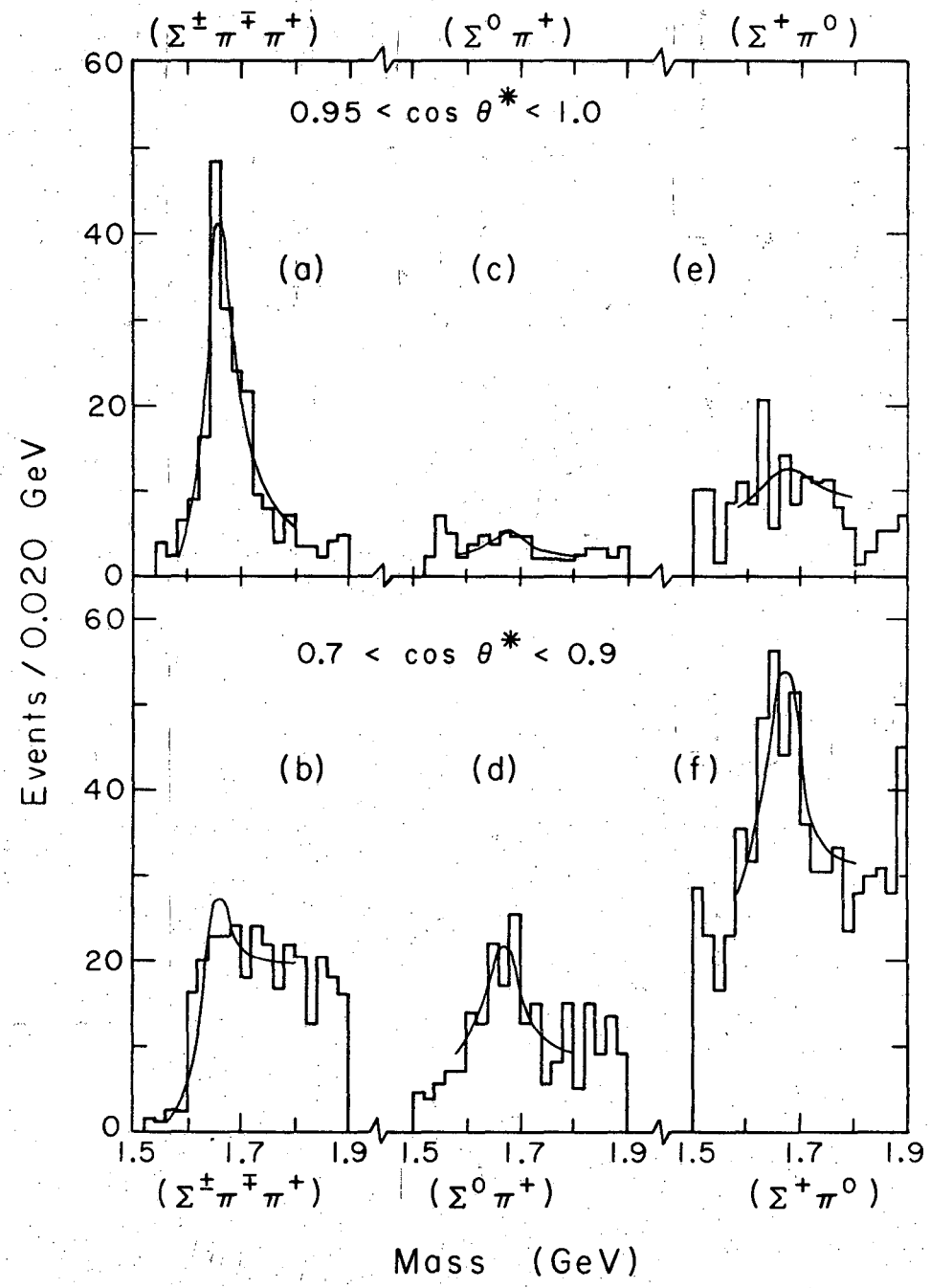

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Fig. 1

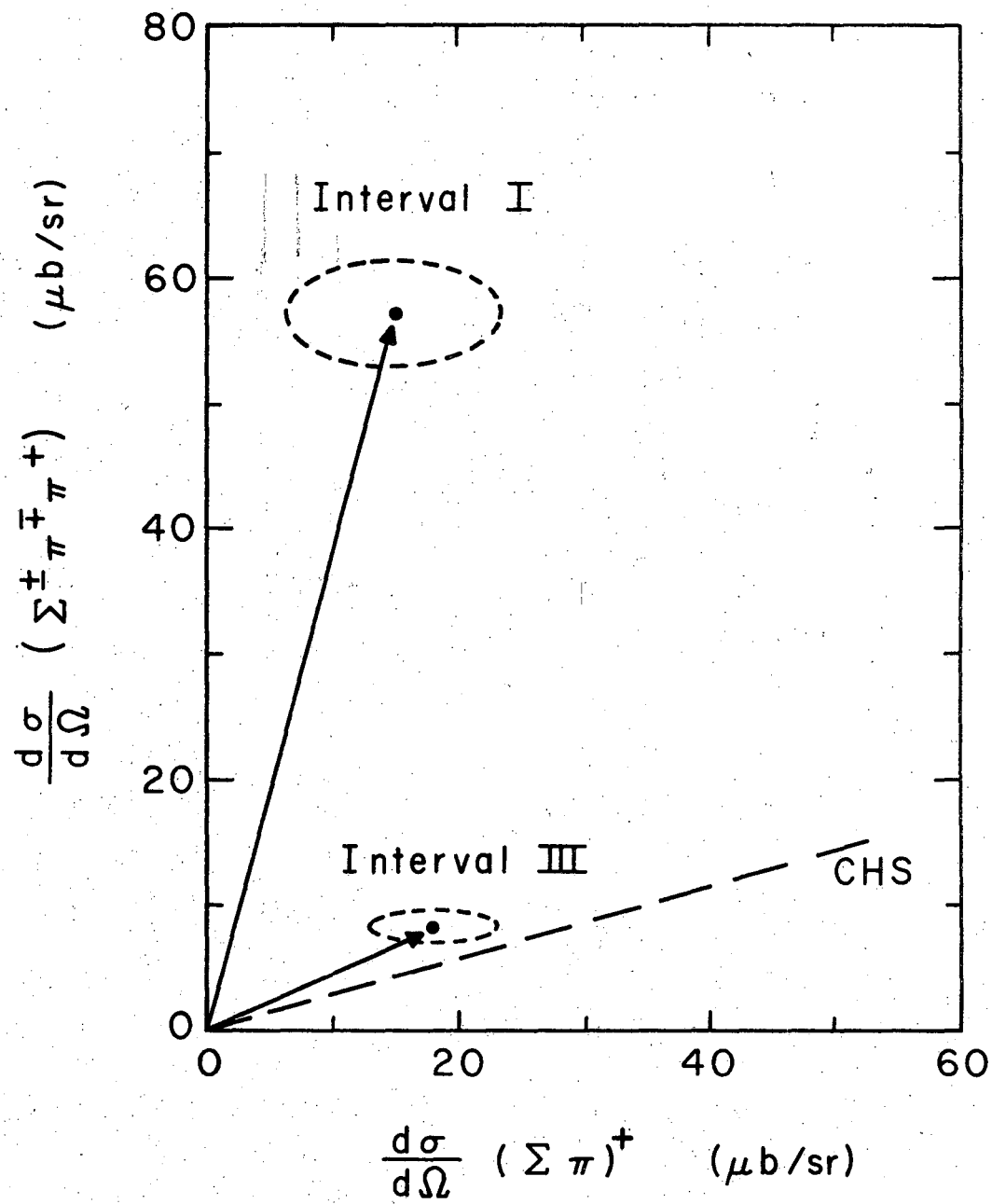

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Fig. 2

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