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Berkeley, California

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November 29, 1962

Evidence for K^* Spin Alignment and Possible Exchange Mechanism in the Reaction $\pi^- p \to \Sigma^0 K^*$ †

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Recently Armenteros et al. presented suggestive evidence that the spin of the K^* resonance[1] is not zero.[2] Subsequently Chinowsky, et al. have concluded that the K^* has spin one and odd spatial parity.[3] In the present Letter we give further evidence, based on a spin-alignment effect, for the K^* spin ≥ 1 as observed in the reaction $\pi^- p \to \Sigma^0 K^*$. In addition we discuss the possibility that K or K^* exchange mechanisms can account for the alignment.

The Lawrence Radiation Laboratory's 72-in. liquid-hydrogen bubble chamber was exposed to a π^- beam resulting in approximately 225,000 pictures of 10 to 20 tracks each. In a systematic analysis of events of the type $\pi^- p \to YK\pi$ at incident momenta of 2.17 and 2.25 BeV/c, we have identified 209 events in the category $\Sigma^0 K^+ \pi^-$. All events were measured and processed through the kinematical constraint program PACKAGE. In most cases identification of the reaction was unambiguous between $\Lambda^0 K^+ \pi^-$ and $\Sigma^0 K^+ \pi^-$. For events that were considered ambiguous the identification was based on χ^2 alone. A detailed study of the relative confidence levels of the fits in this latter category indicated that <10% of the $\Sigma^0 K^+ \pi^-$ sample could possibly be $\Lambda^0 K^+ \pi^-$, although the probable value is estimated to be somewhat less.

In Fig. 1 we present the effective mass-squared distribution for the K-π system in the reaction $\pi^- p \to \Sigma^0 K^+ \pi^-$. The data are consistent with strong K^* production; the non-K^* background is estimated to be less than 30% of the total sample. A mass of 885 MeV and a full width at half-maximum of $\Gamma \sim 50$ MeV are required to fit the data, consistent with previous results on the mass and width of the K^* resonance.[4,5] It should be noted that, in addition to the small background in the sample, this reaction is particularly advantageous for studying K^* properties since the strong Y-π resonances, Y_1^* (1385 MeV), Y_0^* (1405 MeV) and Y_0^* (1520 MeV), are not present in the $\Sigma^0 K^+ \pi^-$ reaction.[6]

In an attempt to observe K^* spin alignment effects we have constructed three angles, α, β, and γ, all of which are measured in the K^* rest system: α is the angle of decay with respect to a unit vector $\hat{n}$ normal to the production plane for the two-body final state; β is the angle of decay with respect to a unit vector $\hat{I}$ along the direction of the incident pion in the K^* rest frame; and γ is the angle of decay with respect to the direction $\hat{I} \times \hat{n}$. These angles define a set of direction cosines in the K^* rest frame. The experimental distributions in these angles are given in Fig. 2.[7] The curves are a result of a maximum-likelihood fit to a polynomial in the cosine of the angle up through the second order. The data in $\cos\alpha$ and $\cos\gamma$ are fit satisfactorily with only terms in even powers of $\cos\alpha$ and $\cos\gamma$ respectively, whereas the distribution in $\cos\beta$ is essentially isotropic. The anisotropies in the data clearly rule out a spin assignment of zero for the K^*.

It is of interest to consider mechanisms that could produce these alignment effects. The simplest diagrams involve K or K^* exchange as indicated in Fig. 3.[8] The K^* decay distributions arising from these diagrams may be considered in terms of the following general arguments based on angular-momentum and parity

conservation. The pseudoscalar nature of the K and π requires an $L = 1^-$ orbital state of the K-π system at vertex II of Fig. 3(a). Therefore, the decay of the K^* with respect to the direction of the incident pion would exhibit a distribution characterized by $\cos^2\beta$, since the orbital projection on this axis is necessarily zero. Turning now to the K^* exchange diagram of Fig. 3(b), we again note that the pion absorption at II must go through an $L = 1^-$ orbital state. This, plus the fact that the total J of the system equals S, the K^* spin, permits us to exclude a state of $m_J=0$, since the $(L = 1, m_L = 0)$ and $(S = 1, m_S = 0)$ states do not couple. Thus, in the final state the K^* spin must be described by the quantum numbers $(J, m_J) = (S, m_S) = (1, -1)$ and $(1, 1)$ and the decay of the K^* would be characterized by $\sin^2\beta$. Since the data are not satisfied by either of these diagrams alone, we have allowed for a mixture of K and K^* exchange. We may write the decay amplitude ψ in this case as

$$\psi = AY_1^1 + BY_1^{-1} + CY_1^0, \qquad (1)$$

where A and B are K^* exchange amplitudes, and C is the K exchange amplitude (in general A, B, and C are functions of μ, the cosine of the center-of-mass production angle of the K^*). Therefore the decay intensity ρ is

$$\begin{aligned}\rho(\mu,\beta,\phi) = {} & \left[(a-b)^2 + 4ab\sin^2(\phi + \tfrac{1}{2}\Gamma_1)\right]\sin^2\beta \\ & + 2\sqrt{2c}\left[b\cos(\Gamma_3-\phi) - a\cos(\Gamma_2+\phi)\right]\sin\beta\cos\beta \\ & + 2c^2\cos^2\beta, \end{aligned} \qquad (2)$$

where a, b, and c are the absolute values of A, B, and C; Γ_1, Γ_2, and Γ_3 are the relative phases of A and B, A and C, and B and C, respectively; and ϕ is the azimuthal angle measured in the plane defined by $\hat{n}$ and $\hat{l}\times\hat{n}$, with $\phi = 0$ along $\hat{n}$.

The complete diagrams of Fig. 3 have been calculated in order to obtain the dependence of A, B, and C upon μ.[9] Integration of Eq. (2) over μ and over the appropriate decay angle (ϕ or $\cos\beta$, respectively) yields the decay angular distributions

$$\rho(\beta) \propto 1 + \left[(2g_0 - 2g_1 - g_4)/(2g_1 + g_4)\right] \cos^2\beta \tag{3a}$$

$$\rho(\phi) \propto 1 + \left[g_4/(2g_1 + g_0 + g_4)\right] \cos 2\phi , \tag{3b}$$

where the g_i are positive definite combinations of form factors. The projection of Eq. (2) onto $\hat{n}$ and $\hat{I}\times\hat{n}$ gives (after integration over μ and over the corresponding azimuths)

$$\rho(\alpha) \propto 1 + \left[(g_1 - g_0 + 2g_4)/(g_1 + g_0)\right] \cos^2\alpha \tag{3c}$$

$$\rho(\gamma) \propto 1 + \left[(2g_1 - g_0 - g_4)/(g_0 + g_4)\right] \cos^2\gamma. \tag{3d}$$

We note that the interference term between K and K^* exchange in Eq. (2) does not contribute to any of the Eqs. (3).

The maximum-likelihood fits to the experimental distributions in $\rho(\beta)$ and $\rho(\gamma)$ (Fig. 2) were used to determine the coefficients g_0, g_1, and g_4 in Eqs. (3a) and (3d) with the results $g_0/g_4 = 0.67 \pm 0.22$ and $g_1/g_0 = 0.37 \pm 0.15$. These values give: (a) a predicted $\rho(\alpha)$ of $1 + (1.74 \pm 0.74)\cos^2\alpha$, in agreement with the corresponding maximum-likelihood fit to the data of $1 + (1.59 \pm 0.55)\cos^2\alpha$; (b) a predicted $\rho(\phi)$ of $1 + (0.48 \pm 0.08)\cos^2\phi$, which is consistent with the data presented in Fig. (4a); and (c) a ratio of 0.45 ± 0.10 for the K to K^* exchange cross sections. These coefficients (plus the relations of footnote (9)) also predict the production angular distribution

$$\rho(\mu) = (a-b)^2 + 2ab + c^2 , \tag{4}$$

which is compared with the data in Fig. (4b). The solid curve corresponds to the

mean values of the maximum-likelihood fits in $\rho(\beta)$ and $\rho(\gamma)$; the dotted curve corresponds to these values each shifted by one standard deviation upward in magnitude from the mean. Both the assumption of a background isotropic in production and decay angles, and the normal variation of the form factors, would tend to bring the solid curve of Fig. (4b) into better agreement with the data, but we are unable to provide quantitative estimates of these factors. We conclude that a combination of K and K^* exchange satisfies the major features of the data.

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FOOTNOTES AND REFERENCES

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6. The best currently available information on the branching ratio

$$\frac{\Gamma(Y_1^* \to \Sigma\pi)}{\Gamma(Y_1^* \to \Lambda\pi) + \Gamma(Y_1^* \to \Sigma\pi)}$$

gives $\lesssim 6\%$ [see P. Bastien, M. Ferro-Luzzi, and A. H. Rosenfeld, Phys. Rev. Letters 6, 702 (1961)]. Based on approximately 57 events which we attribute to

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$Y_1^* \to \Lambda^0\pi^-$ the expected number $Y_1^* \to \Sigma^0\pi^-$ is $\lesssim 4$. An analysis of the $\Sigma^0\pi^-$ mass distribution for our 209 Σ^0 events indicates no significant enhancement in the region of 1385 MeV, consistent with the expectation.

7. We have considered Λ^0 and Σ^- events and find that the distributions in $\cos\alpha$, $\cos\beta$, and $\cos\gamma$ are qualitatively dissimilar from those of the Σ^0 events. The interpretation of these distributions is confused by the presence of the strong Y-π resonances. The Σ^+ events cannot contribute to this analysis since the K-π system is in a pure $I = 3/2$ state. An analysis of only those Σ^0 events in a very narrow band defined by $0.73 \leq M^2(k\pi) \leq 0.82\ \mathrm{BeV}^2$ indicates no qualitative differences between this sample and all 209 events.

8. It should be noted that similar diagrams can be constructed for Λ^0K^* production, whereas this is not the case for Σ^-K^* production since the latter requires an exchange particle of $I_z = 3/2$.

9. At a π^-p center-of-mass energy of 2.25 BeV (2.21-BeV/c pion laboratory momentum) a calculation of the complete diagrams of Fig. 3 gives

$$4ab = (g_2 - g_3\mu)(1-\mu^2)\,(1-0.434\mu)^{-2}, \tag{1}$$

$$(a-b)^2 = g_1(1-0.72\mu), \tag{2}$$

$$2c^2 = g_0(1-0.35\mu), \tag{3}$$

and

$$\Gamma_1 = \pi, \tag{4}$$

where

$$g_0 = \left|F_{KK^*\pi}(k^2)\,F_{P\Sigma K}(k^2)\right|^2 \tag{5}$$

$$g_1 = \left|F_{K^*K^*\pi}(k^2)\right|^2 \left|F_1(k^2) - F_2(k^2)\right|^2 \tag{6}$$

$$g_2 = \left|F_{K^*K^*\pi}(k^2)\right|^2 \left[(1.756)\left|F_1\right|^2 + (0.392)\left|F_2\right|^2\right] \tag{7}$$

and

$$g_3 = \left|F_{K^*K^*\pi}(k^2)\right|^2 \left[(0.299)\left|F_2\right|^2\right]. \tag{8}$$

The $P\Sigma K^*$ interaction is the form $F_1\gamma^\mu + i\lambda^{-1}F_2\sigma^{\mu\nu}k_\nu$, where k_ν is the K^* momentum and we have $\lambda = M_P + M_\Sigma$. Here g_1, g_2 and g_3 are not entirely independent, and with the analysis of this paper we find $g_3/g_2 = 0.22 \pm 0.06$. The average (over μ) of 4ab gives

$$g_4 = 0.755\, g_2 - 0.138\, g_3 \,. \tag{9}$$

FIGURE LEGENDS

Fig. 1. $M^2(K\pi)$ for 209 $\Sigma^0 K^+\pi^-$ events at incident pion momenta of 2.17 and 2.25 BeV/c. The curve represents a Breit-Wigner resonance form for the K^* with mass 885 MeV and full width at half maximum Γ = 50 MeV weighted with nonresonant phase space (70% K^*, 30% phase space).

Fig. 2. (a) K^* decay relative to the normal, $\hat{n}$, to the $\Sigma^0 K^*$ production plane. The curve is an independent maximum-likelihood fit of the form $1 + (1.59 \pm 0.55)\cos^2\alpha$ with a χ^2 value of 2.4 for eight degrees of freedom. (b) K^* decay relative to $\hat{I}$, the direction of the incident pion in the K^* rest frame. The curve is an independent maximum-likelihood fit of the form $1 - (0.11 \pm 0.21)\cos^2\beta$ with a χ^2 value of 2.7 for eight degrees of freedom. (c) K^* decay relative to $\hat{I}\times\hat{n}$. The curve is of the form $1 - (0.74 \pm 0.11)\cos^2\gamma$ with a χ^2 value of 12.9 for eight degrees of freedom.

Fig. 3. Possible diagrams contributing to $\Sigma^0 K^*$ production.

Fig. 4. (a) Azimuthal distribution of the K^* decay measured in the plane defined by $\hat{n}$ and $\hat{I}\times\hat{n}$. Here $\phi = 0$ is selected along $\hat{n}$. The curve is of the form $1 + (0.48 \pm 0.08)\cos^2\phi$ as predicted by the exchange model discussed in the test. The fit has a χ^2 value of 3.8 for ten degrees of freedom. (b) Angular distribution of the K^* in the production center of mass. The solid curve represents the prediction of the exchange model discussed in the test; the dotted curve is one standard-deviation shift from the solid curve.

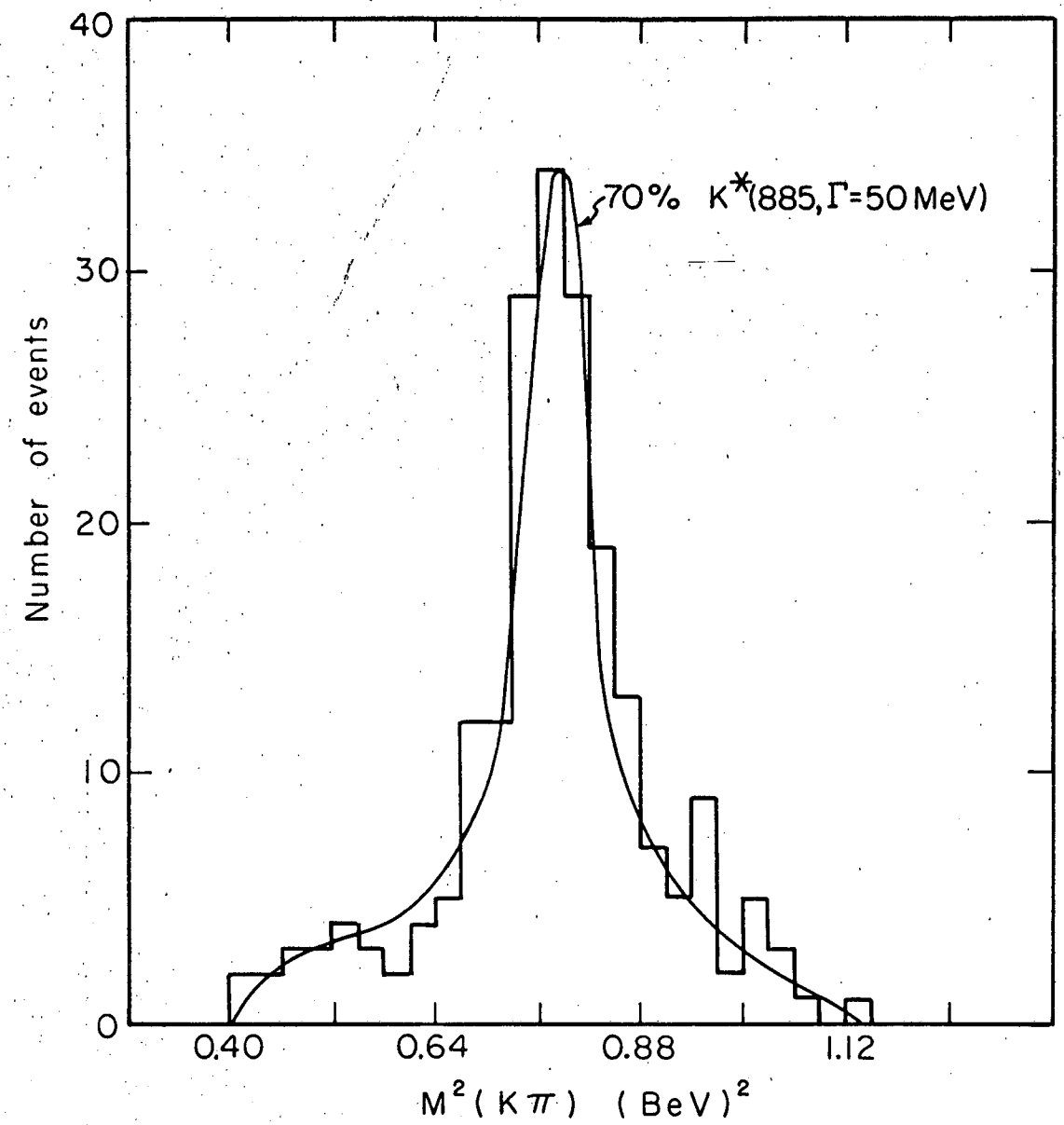

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Fig. 1

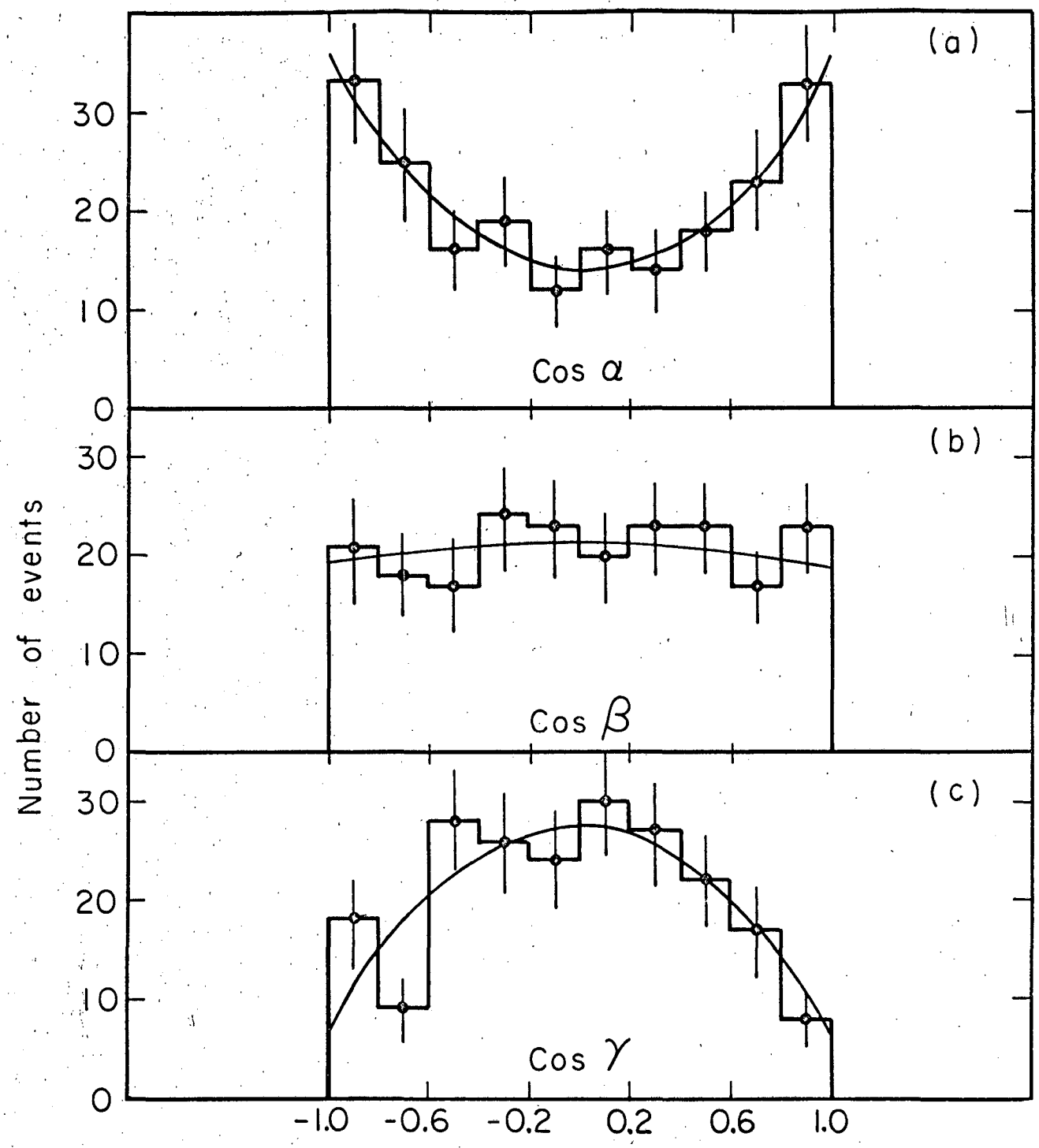

Fig. 2

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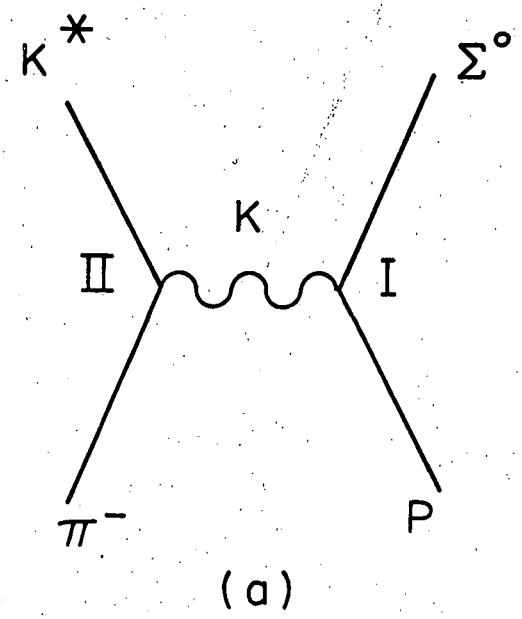
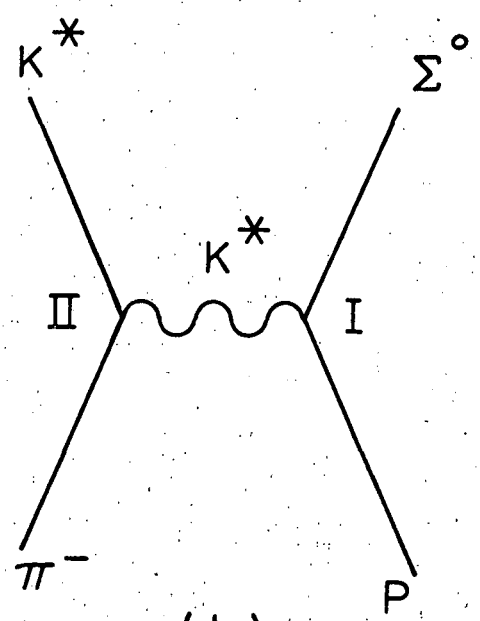


(a)



(b)

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Fig. 3

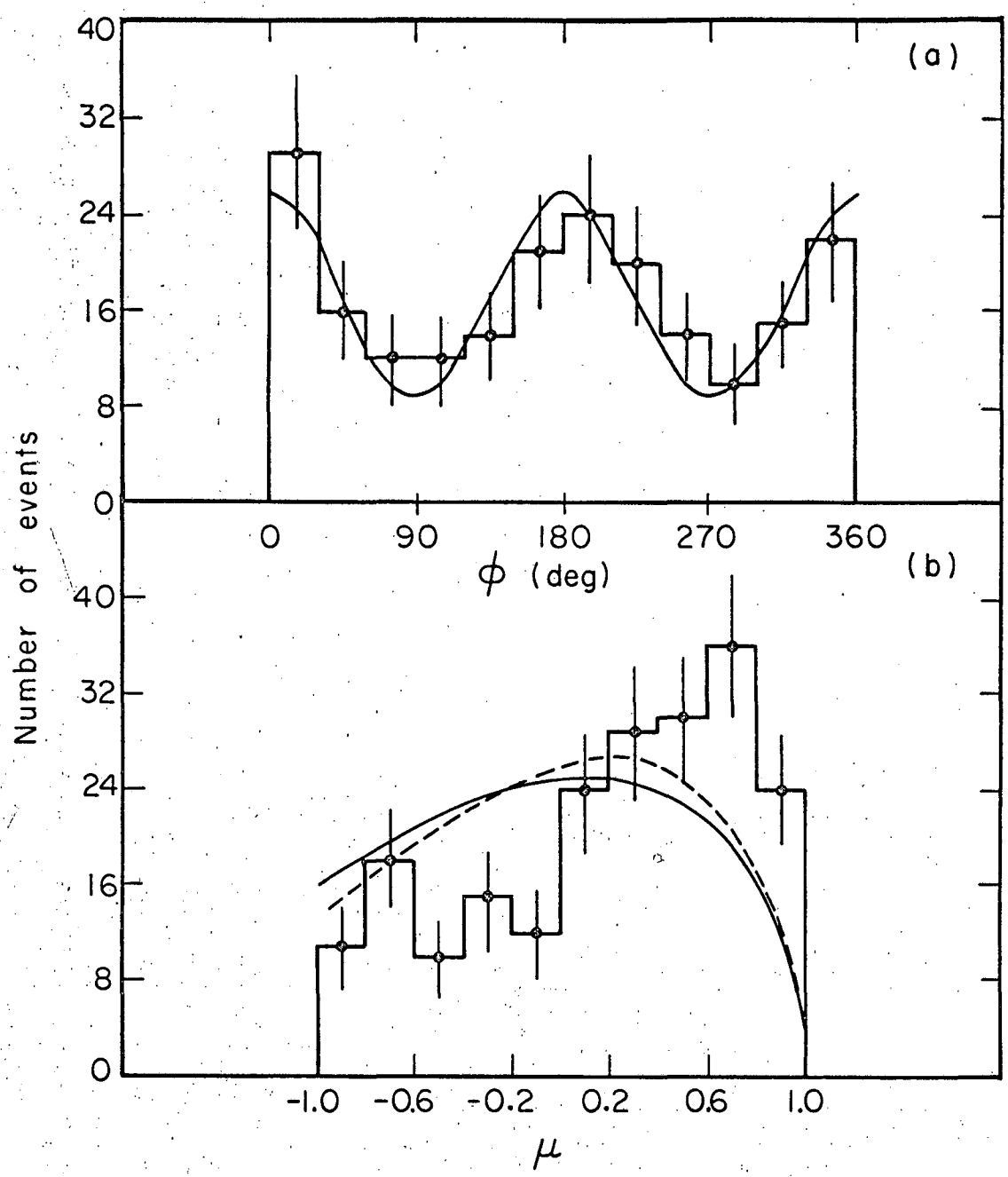

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Fig. 4