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Publication Date
1966-07-08
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Submitted to Phys. Rev. Letters

UNIVERSITY OF CALIFORNIA
Lawrence Radiation Laboratory
Berkeley, California
AEC Contract No. W-7405-eng-48

STUDY OF $Y_1^*$ RESONANT AMPLITUDES
BETWEEN 1660 AND 1900 MeV

Wesley M. Smart, Anne Kernan, George E. Kalmus,
and Robert P. Ely, Jr.
July 8, 1966
Study of $Y_1^*$ Resonant Amplitudes between 1660 and 1900 MeV*

Wesley M. Smart, Anne Kernan, George E. Kalmus, and Robert P. Ely, Jr.

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ABSTRACT

A partial-wave analysis of the reaction $K^- n \rightarrow \Lambda \pi^-$ has confirmed the spin-parity assignments for $Y_1^*(1765)$ and $Y_1^*(2030)$ and measured the mass, width, and $\Lambda \pi$ branching ratio of $Y_1^*(1765)$ as $1776 \pm 6$ MeV, $129 \pm 16$ MeV and $0.14 \pm 0.02$, respectively. A tentative spin-parity assignment for $Y_1^*(1660)$ and $Y_1^*(1915)$ is also made.
The cross section for the pure isotopic-spin $I = 1$ channel $K^- + p \rightarrow \Lambda + \pi^0$ in the c.m. energy interval 1660 to 1900 MeV shows a broad rise centered around 1780 MeV. We have analyzed the angular distributions and polarizations in the reaction $K^- + n \rightarrow \Lambda + \pi^-$ in this energy interval, in order to study $Y_1^*$ resonant amplitudes in the $\Lambda\pi$ channel.

The known $I = 1$ resonances between 1660 and 1900 MeV are $Y_1^*(1660)$ and $Y_1^*(1765)$. In addition, amplitudes due to $Y_1^*(1915)$ and $Y_1^*(2030)$ may be present in the energy interval under study.

$Y_1^*(1660)$. This resonance has $J = 3/2^-$, $x_{\Lambda \pi} \approx 0.05$, where $x_R$ is the branching ratio in the channel $R$. The parity is uncertain.

$Y_1^*(1765)$. The assignment $I, J^P = 1, 5/2^-$ has been deduced from a study of the reaction $K^- + \text{nucleon} \rightarrow Y_0^*(1520) + \pi$; $x_{\Lambda \pi} = 0.5$, and $x_{\Lambda \pi}$ is not known.

$Y_1^*(1915)$. This resonance was recently discovered as a bump in the $K^-n$ total cross section; $(J + 1/2) x_{\Lambda \pi} = 0.31$, but $J$, $P$ and $x_{\Lambda \pi}$ are unknown.

$Y_1^*(2030)$. A study of the reactions $K^- + p \rightarrow \Lambda + \pi^0$ and $K^- + p \rightarrow \bar{K}^0 + n$ in the $K^-$ momentum interval 1220 to 1700 MeV/c has given $I, J^P = 1, 7/2^+$, with $x_{\Lambda \pi} = 0.25$ and $x_{\Lambda \pi} = 0.16$.

The analysis described below leads to the following results:

(i) The bump at 1780 MeV in the cross section for $K^- + \text{nucleon} \rightarrow \Lambda + \pi$ is due to a $Y_1^*$ resonance of mass $1776 \pm 6$ MeV, width $129 \pm 16$ MeV, $J^P = 5/2^-$, and $x_{\Lambda \pi} = 0.14 \pm 0.02$. We identify this resonance with $Y_1^*(1765)$ and confirm the previous $I J^P$ assignment.
(ii) We verify that the parity of $Y_1^*(2030)$ is positive.

(iii) The parity of $Y_1^*(1660)$ is probably negative; a conclusive parity determination is not possible because the $Y_1^*(1660)$ amplitude is relatively weak in the $\Lambda\pi$ channel and there is insufficient data around 1660 MeV in this experiment.

(iv) There are some indications that $j^P = 5/2^+$ and $x_{\Lambda\pi} = 0.12 \pm 0.08$ for $Y_1^*(1915)$. This spin-parity assignment would make $Y_1^*(1915)$ a candidate for the Regge recurrence of the $\Sigma$ hyperon.

(v) We observe that the relative phase $\phi$ of $Y_1^*(1765)$ and $Y_1^*(2030)$, each at the resonant energy, is $162 \pm 9$ deg; this phase difference is always 0 deg in the elastic channel. It also seems probable that $Y_1^*(1765)$ is in phase with $Y_1^*(1915)$ at the resonant energy, but $180$ deg out of phase with $Y_1^*(1660)$. These observations can be related to the relative signs of the coupling constants $\mathcal{g}_{KNY^*}$ and $\mathcal{g}_{\Lambda\pi Y^*}$, as discussed below.

**EXPERIMENTAL DETAILS**

A total of 22,000, 75,000, 63,000 and 91,000 pictures of $K^-$-deuterium interactions at 815, 915, 1015, and 1110 MeV/c, respectively, were taken in the Lawrence Radiation Laboratory's (LRL) 25-in. bubble chamber. The average beam intensity was 9 $K^-$ per picture.

We measured 23,580 events having the topology of the interaction sequence

$$K^- + d \rightarrow \Lambda + \pi^- + p_1, \, \Lambda \rightarrow \pi^- + p,$$

with momentum of the proton $p_1$ between 0 and 230 MeV/c. The track of $p_1$ was not measurable below 90 MeV/c; 6294 events had a measurable proton ($p_1$) track. The events were measured on the LRL Flying-Spot Digitizer (4984 events) and on a Franckenstein (18,596 events).
A total of 4117 events fitted the reaction (1) hypothesis, and lay within the assigned fiducial region. The momentum distribution of the protons $p_1$ agrees with the Hulthen form of the deuteron wave function, and, therefore, we assume that the observed interaction is $K^- + n \rightarrow \Lambda\pi^-$, with the proton in the role of spectator. The only contamination is the reaction $K^- + n \rightarrow \Sigma^0 + \pi^-$, which comprises less than 10% of our sample.

Figure 1 shows the measured angular distribution of the pion and the $\Lambda$ polarization in the reaction $K^- + n \rightarrow \Lambda + \pi^-$. The data is divided into 10 intervals in c.m. energy; the c.m. energy was taken as the magnitude of the four-momentum of the $\Lambda\pi^-$ system. Each event in the angular distribution was weighted by the factor $1/(P_p S_\pi S_\Lambda)$, where $P_p$ is the probability of the $\Lambda$ decaying within the fiducial volume and ranges from 0.71 to 0.97 depending on the momentum of the $\Lambda$ and the position of the $K^-$ interaction vertex. The factor $S_\pi$, which varies from 0.6 to 1.0, corrects for scanning bias involving events in which $\pi^-$ is almost collinear with $K^-$. Scanning bias against certain configurations of $\Lambda$ decay is accounted for by $S_\Lambda$, which is a function of lambda momentum and varies from 0.93 to 0.96. The observed angular distributions were converted to differential cross sections by using the published cross sections for the reaction $K^- + p \rightarrow \Lambda + \pi^0$. The polarization of the $\Lambda$ was calculated from the observed $\Lambda$-decay asymmetry relative to the production normal $\hat{n} = \hat{K} \times \hat{p}_1 / |\hat{K} \times \hat{p}_1|$, according to the formula $P_\Lambda \cdot \hat{n} = 3 a_\Lambda \langle \hat{p} \cdot \hat{n} \rangle$, where $\hat{p}$ is a unit vector parallel to the momentum of the proton in $\Lambda$ decay, and $a_\Lambda$ is 0.66.
ANALYSIS

The angular and polarization distributions may be expressed in the form:

\[ \frac{d\sigma}{d\Omega} = \lambda^2 \sum_m A_m P_m(\hat{K} \cdot \hat{n}) \]

(2)

\[ \left( \frac{d\sigma}{d\Omega} \right) P = \hat{n} \cdot \lambda^2 \sum_m B_m P_m^1(\hat{K} \cdot \hat{n}), \]

(3)

where \( P_m(\hat{K} \cdot \hat{n}) \) is the Legendre polynomial of order \( m \), \( P_m^1(\hat{K} \cdot \hat{n}) \) is the first associated Legendre polynomial and \( \lambda \) is the incident c.m. wavelength divided by \( 2\pi \). The quantities \( A_m \) and \( B_m \) are functions of the complex transition amplitudes \( T_{\ell}^\pm \) for states with \( J = \ell \pm 1/2 \), and \( \sigma = 4\pi \lambda^2 A_0 \).

Coefficients \( A_m \) and \( B_m \) were determined by fitting the experimental distributions in Fig. 1 to Eqs. (2) and (3) by using the method of least squares. Figure 2 shows \( A_m/A_0 \) and \( B_m/A_0 \) plotted against c.m. energy; the coefficients are divided by \( A_0 \) so that the figure shows only the information learned in this experiment.

Certain deductions can be made from the A and B coefficients in Fig. 2. All the data can be fitted by an expansion to \( m \leq 6 \), indicating that amplitudes with \( J > 7/2 \) are not required in this energy region. The absence of an \( A_7 \) coefficient shows that only one amplitude with \( J = 7/2 \) is required to fit the data. The rapid energy variation of the A coefficients suggests that at least one resonant amplitude is strongly present.

As already noted, the total cross section for \( K^- + \text{nucleon} \to \Lambda + \pi \) shows a pronounced bump at 1780 MeV. This is most likely due to \( Y_1(1765) \) with \( J^P = 5/2^- \). In support of this hypothesis we note that \( A_2 \) and \( A_4 \)
are large and positive in the energy region where the total cross section peaks, whereas $A_6$ is insignificant. This observation suggests a $J = 5/2$ amplitude, since the square of an amplitude with spin $J$ makes a positive contribution to $A_m$ for all even $m$ with $m < 2J$.

To obtain more quantitative information on the amplitudes present in the $\Lambda\pi$ channel, we made a computer search for the set of partial-wave amplitudes which best fitted the polarization and differential cross sections in Fig. 1.

Table I lists the sets of amplitudes assumed in different fits. In fits 1, 2, and 3 we assume four nonresonant amplitudes $S_1$, $P_1$, $P_3$, and $D_3$, since analyses of the $\Lambda\pi$ channel in the c.m. interval 1600 to 1700 MeV have established the presence of $S_1$, $P_1$ and at least one $J = 3/2$ background amplitudes.\(^7\)\(^{,}\)\(^{,}\)\(^{,}\)^{1c,1d} The energy dependence of these amplitudes is not known, and we hypothesize that they are constant over the energy region. The magnitudes and phases of these amplitudes were allowed to vary in all the fits.

In order to test for the presence of $Y_4^{+}(1765)$ with $J = 5/2$ in the $\Lambda\pi$ channel, the four nonresonant amplitudes were combined with a single $5/2^-$ (D-wave) resonant amplitude in fit 1a, and with a single $5/2^+$ (F-wave) resonant amplitude in fit 1b.

The resonant amplitudes had the Breit-Wigner form

$$T = \frac{1}{Z} \left( \Gamma_{RN} \Gamma_{\Lambda\pi} \right)^{1/2} / (E_R - E - i \Gamma/2) \text{ with } \Gamma_{1} = \alpha (q_1^2/(q_1^2 + X^2)) f_1(q_1/E)$$

and $\Gamma = \sum_i \Gamma_i$. The summation is over all decay channels of the resonance; $X$ is fixed at 350 MeV, and $q_1$ and $f_1$ are the momentum and orbital angular momentum of the decay products of the resonance of energy $E$ in channel $i$.\(^8\) In fit 1 and succeeding fits, the mass $E_R$. 
width $\Gamma$, and the magnitude at the resonant energy $x_{KN} \cdot x_{\Lambda\pi}$
($= \Gamma_{KN} \cdot \Gamma_{\Lambda\pi}/\Gamma^2$) of the $J = 5/2$ resonant amplitude were allowed to vary.

The differential cross sections and polarizations predicted by each set of amplitudes 1a and 1b were compared with the experimental data and the $\chi^2$ function computed. The $\chi^2$ was a function of 11 variables --the magnitudes and phases of the four nonresonant amplitudes, and the mass, width, and magnitude of the resonant amplitude. One phase is arbitrary, and this was fixed by making the $J = 5/2$ resonant amplitude purely imaginary at $E = E_R$ (this convention was used in all fits). The program VARMIT was used to search through the hyperspace of 11 variables for the minimum in $\chi^2$.

The solutions that minimize $\chi^2$ for the 1a and 1b hypotheses are shown in Fig. 3, a and b, and the final $\chi^2$ is listed in Table I. The resonant $D_5$ amplitude is clearly favored over the resonant $F_5$ amplitude, but both solutions are highly improbable. Although both sets of amplitudes in fit 1 are inadequate to fit the data, it is instructive to examine the A and B coefficients generated by each solution; these are drawn in on Fig. 2. The manner in which the experimental data discriminates between the $F_5$ and $D_5$ hypotheses is clearly illustrated by the $A_2$ and $B_2$ coefficients. In terms of the partial-wave amplitude $A_2$ and $B_2$ are expressed as:

$$A_2 = \text{Re} \left[ 2( |P_3|^2 + |D_3|^2) + (24/7) \left( |D_5|^2 + |F_5|^2 \right) + 4 (S_4^* D_3 + P_4^* P_3) + 6 (S_4^* D_5 + P_4^* F_5) + (12/7) \right]$$

$$\left( P_3^* F_5 + D_3^* D_5 \right)$$
\[ B_2 = \text{Im} \left[ 2(S_1^*D_3 - P_1^*P_3) - 2(S_1^*D_5 - P_1^*F_5) + \frac{10}{7} \right] (P_3^*F_5 - D_3^*D_5) \].

The terms in \( A_2 \) are the scalar products of the corresponding vectors in Fig. 3; the terms in \( B_2 \) are the vector products. The energy dependence of \( A_2 \) is equally well reproduced by the \( S_1^* \) and \( D_5 \) amplitudes in Fig. 3a or by the \( P_1^* \) and \( F_5 \) amplitudes in Fig. 3b. But only the \( S_1^*, D_5 \) interference gives the correct sign for the \( B_2 \) coefficient.

The expansion for \( A_4 \) is
\[ A_4 = \text{Re} \left[ (18/7) \left( |D_5|^2 + |F_5|^2 \right) + \frac{72}{7} (P_3^*F_5 + D_3^*D_5) \right] . \tag{4} \]

The energy dependence of \( A_4 \) is well described by the \( D_3 \) and \( D_5 \) amplitudes in Fig. 3a, but not by the \( P_3 \) and \( F_5 \) amplitudes in Fig. 3b.

In fit 2 we added to the amplitudes in fit 1 the \( J = 7/2 \) resonant amplitude due to \( Y_1^+(2030) \). According to references 4 and 5, we fixed the mass and width at 2035 MeV and 160 MeV, respectively; our data are insensitive to these parameters since the resonant energy is far removed from the energy region under study. The data are sensitive, however, to the parity of \( Y_1^+(2030) \), and this was checked by trying both the \( J^P = 7/2^+ \) (F-wave) and \( 7/2^- \) (G-wave) hypothesis. The magnitude and phase of \( Y^+(2030) \) were allowed to vary, thus increasing the number of variables from 11 to 13. The only acceptable solution is 2a, which requires negative parity for the \( J = 5/2 \) resonant amplitude and positive parity for the \( J = 7/2 \) resonant amplitude. Solution 2a gives 1777 ± 6 and 135 ± 16 MeV respectively for the mass and width of the \( 5/2^- \) resonance. Therefore, we identify this resonance with \( Y_4^+(1765) \) and confirm the previous determination of \( \Gamma, J^P = 1, 5/2^- \). This parity
solution for $Y_1^*$ \textit{(2030)} agrees with the recent measurement of Wohl, Solmitz, and Stevenson. 5

Solution 2a is shown in Fig. 3c. This set of amplitudes cannot generate the negative $A_6$ coefficient observed at 1855 MeV. The interference terms $D_5$, $G_7$, and $F_7$, $F_7$ are responsible for a negative $A_6$ coefficient. Since the single $J = 7/2$ amplitude present has been identified as $F_7$, an $F_5$ amplitude is indicated; a $G_7$ amplitude would generate an $A_7$ coefficient which is not required to fit the data. The negative $A_6$ coefficient is most marked at 1855 MeV; $A_4$ is negative at this energy, showing that $|F_5|^2$ in Eq. (4) is small. The fact that $F_5$ is relatively weak makes it impossible to determine whether or not this amplitude is resonant. However, we speculate that this amplitude may correspond to the recently discovered $Y_1^*(1915)$. 4 In fit 3 an $F_5$ amplitude of mass 1915 MeV and width 65 MeV was added to the $D_5$ and $F_7$ resonant amplitudes. The solution is shown in Fig. 3d. The $\chi^2/N$ value for this fit is (226/196); the equivalent probability is 0.07.

Table II summarizes the parameters of $Y_1^*(1765)$, $Y_1^*(2030)$, and $Y_1^*(1915)$ determined with varying degrees of certainty in fits 2 and 3. Fit 3 gives 1776 and 129 MeV respectively for the mass and the width of $Y_1^*(1765)$, together with the value of $(xKNx_{\Lambda\pi})$ for the three states. Using the published values of $x_{KN}$ we determine the branching ratio $x_{\Lambda\pi}$ for $Y_1^*(1765)$ and $Y_1^*(1915)$ into the $\Lambda\pi$ channel. The branching ratio $x_{\Lambda\pi}$ for $Y_1^*(2030)$ is $0.55 \pm 0.20$, in disagreement with reference 5. The disagreement is not surprising, since it is not known whether the energy dependence assumed for $\Gamma$ is valid for energies about $2\Gamma$ below the resonant energy. 8, 11
The errors quoted in Table II are the statistical errors calculated in our fitting program, increased by a factor of two. The statistical errors have been doubled in an attempt to include uncertainties arising from the assumptions (a) that there are no nonresonant amplitudes present with the same spin and parity as the resonances, (b) that the background amplitudes are constant, and (c) that the energy dependence used for $\Gamma$ may not be exactly correct.

Until now we have neglected $Y_4^*(1660)$ because its amplitude in the $\Lambda\pi$ channel is weak. In fits 4a and 4b we took the experimental data below 1800 MeV, where the $Y_4^*(1660)$ amplitude is more important, and we made the assumption that one of the $J = 3/2$ amplitudes was due to a resonance of mass 1660 MeV and width 44 MeV. The magnitude and phase of the $J = 3/2$ resonance were allowed to vary. Only the $3/2^-$ resonant hypothesis led to a satisfactory fit; the corresponding $x_{KN} x_{\Lambda\pi}$ value is given in Table II. However, the data below 1800 MeV is almost equally well described by constant $3/2^-$ and $3/2^+$ amplitudes as shown by fit 4c, so that the $J^P = 3/2^-$ assignment is not conclusive.

**COUPLING CONSTANTS $g_{KN^*}$ AND $g_{\Lambda\pi^*}$**

The resonant $D_5$ amplitude was defined to be purely imaginary at $E = E_R$. The phase angles $\phi$ of the other resonant amplitudes at the resonant energies, relative to $D_5$ are shown in Table II. In the elastic channel $\phi$ is always zero; in the inelastic channel it may be zero or 180 deg because the sign of the off-diagonal $T$ matrix elements is undefined. The resonant amplitude in the elastic channel is proportional to $g_{KN}^2/(E_R - E - i \Gamma/2)$ and in the $\Lambda\pi$ channel to $g_{KN^*} g_{\Lambda\pi^*}/(E_R - E - i \Gamma/2)$. For the elastic amplitude the
numerator is always positive; in the inelastic channel the sign of the numerator depends on the relative sign of the coupling constants $\bar{K}_{\pi N}^*$ and $\bar{A}_{\pi Y}^*$. The values of $\phi$ in Table II are consistent with $\phi = 180$ deg for $Y_1^*(2035)$ and $Y_1^*(1660)$, and $\phi = 0$ for $Y_1^*(1915)$. This shows that the product of the coupling constants $\bar{K}_{\pi N}^* \bar{A}_{\pi Y}^*$ is of one sign for $Y_1^*(1765)$ and $Y_1^*(1915)$ and of the opposite sign for $Y_1^*(1660)$ and $Y_1^*(2030)$. The ambiguity arises because the overall orientation of the amplitudes in the $\Lambda\pi$ channel relative to the $K\pi$ channel cannot be determined by this analysis.

We note that the phase of the conjectured $Y_1^*(1915)$, $J^P = 5/2^+$, amplitude in fit 3 is $6 \pm 18$ deg, in agreement with the requirement that the phase $\phi$ be 0 or 180 deg. The resonant nature of the $F_5$ amplitude is supported by this observation.

Acknowledgments

We thank Professors J. S. Ball, G. L. Shaw, and R. D. Tripp for discussions regarding the properties of resonant amplitudes. Eric Beals of the Lawrence Radiation Laboratory computing center advised on mathematics and programming. We are indebted to the Data Processing Group under Howard White and the scanning and measuring staff under Paul W. Weber. We thank the other members of the Powell-Birge Group, in particular Jack Sahouria, for their assistance in this experiment.
Footnotes and References

*Work sponsored by the U. S. Atomic Energy Commission and the National Science Foundation.


9. The program VARMIT was written at Lawrence Radiation Laboratory by E. R. Beals. The input to the program is the \(\chi^2\) function and the analytic partial derivatives of \(\chi^2\) with respect to all the variables. The minimum is found by the Variable Metric method of W. C. Davidson, Argonne National Laboratory, 5990 (Rev. 1959). Approximately two minutes of time is required on the CDC 6600 computer to find the minimum of a function of 15 variables.
UC-34a
STUDY OF $\gamma^*$ RESONANT AMPLITUDES BETWEEN 1660 AND 1900 MeV. Smart, Wesley M.; Kernan, Anne; Kalmus, George E. and Ely, Robert P. Jr. (Lawrence Radiation Lab., Univ. of California, Berkeley) July 8, 1966. 23p.
10. To check the uniqueness of solution 1(a) we used the search mode of the program MINFUN, written by W. E. Humphrey, to look for low regions in the 11-variable hypersurface. A total of 25 low points were used as starting values for the program VARMIT. In all cases the same solution (Fig. 3a) was obtained.

11. The value of \( X = 175 \text{ MeV} \) in the expression 
\[
\Gamma_i \propto [q_i^2/(q_i^2 + X^2)]^{\ell_i} (q_i/E) 
\]
gives a better fit to the data than \( X = 350 \text{ MeV} \) and brings the value of \( x_{\Lambda\pi} \) for \( Y_4^*(2030) \) into closer agreement with the measurement of Wohl et al.

12. An analysis of about 20 events in the reaction \( \pi^+ p \rightarrow \Sigma^\pm \pi^\mp + K^\mp \) at \( 3.23 \text{ BeV/c} \) favors \( J^P = 3/2^- \) for \( Y_4^*(1660) \), Y. Y. Lee, D. D. Reeder, and R. W. Hartung, Phys. Rev. Letters 17, 45 (1966).

13. The connection between the signs of the coupling constants and the SU3 classification of the \( Y_4^* \) resonances will be examined in a forthcoming publication.
Table I. Partial-wave amplitudes used for a least-squares fit to the experimental distributions in Fig. 1. The \( \chi^2 \) for each fit and the corresponding probability are also listed.

<table>
<thead>
<tr>
<th>Fit</th>
<th>Constant amplitudes</th>
<th>Resonant amplitudes</th>
<th>( \chi^2 )</th>
<th>Degrees of freedom</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>( S_4, P_1, P_3, D_3 )</td>
<td>( D_5 )</td>
<td>359</td>
<td>200</td>
<td>( 4 \times 10^{-12} )</td>
</tr>
<tr>
<td>1b</td>
<td>( S_4, P_1, P_3, D_3 )</td>
<td>( F_5 )</td>
<td>724</td>
<td>200</td>
<td>( &lt; 10^{-20} )</td>
</tr>
<tr>
<td>2a</td>
<td>( S_4, P_1, P_3, D_3 )</td>
<td>( D_5, F_7 )</td>
<td>240</td>
<td>198</td>
<td>0.02</td>
</tr>
<tr>
<td>2b</td>
<td>( S_4, P_1, P_3, D_3 )</td>
<td>( D_5, G_7 )</td>
<td>353</td>
<td>198</td>
<td>( 10^{-11} )</td>
</tr>
<tr>
<td>2c</td>
<td>( S_4, P_1, P_3, D_3 )</td>
<td>( F_5, F_7 )</td>
<td>717</td>
<td>198</td>
<td>( &lt; 10^{-20} )</td>
</tr>
<tr>
<td>2d</td>
<td>( S_4, P_1, P_3, D_3 )</td>
<td>( F_5, G_7 )</td>
<td>581</td>
<td>198</td>
<td>( &lt; 10^{-20} )</td>
</tr>
<tr>
<td>3</td>
<td>( S_4, P_1, P_3, D_3 )</td>
<td>( D_5, F_5, F_7 )</td>
<td>226</td>
<td>196</td>
<td>0.07</td>
</tr>
<tr>
<td>4a</td>
<td>( S_4, P_1, P_3 )</td>
<td>( D_3, D_5, F_7 )</td>
<td>148</td>
<td>120</td>
<td>0.04</td>
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<tr>
<td>4b</td>
<td>( S_4, P_1, D_3 )</td>
<td>( P_3, D_5, F_7 )</td>
<td>172</td>
<td>120</td>
<td>( 10^{-3} )</td>
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<tr>
<td>4c</td>
<td>( S_4, P_1, P_3, D_3 )</td>
<td>( D_5, F_7 )</td>
<td>150</td>
<td>120</td>
<td>0.03</td>
</tr>
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Table II. Parameters and quantum numbers of $Y_1^*(1660)$, $Y_1^*(1765)$, $Y_1^*(1915)$, and $Y_1^*(2030)$. The quantities measured or verified in this experiment are underlined with a solid line; quantities suggested by this experiment are indicated by a broken line.

<table>
<thead>
<tr>
<th>Mass $E_R$ (MeV)</th>
<th>Width $\Gamma$ (MeV)</th>
<th>Spin $J$</th>
<th>Parity $\pi$</th>
<th>$x_{\pi KN}$</th>
<th>$x_{\pi \Lambda N}$</th>
<th>$x_{\Lambda KN}$</th>
<th>$x_{\Lambda \pi}$</th>
<th>$\phi$ (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1660</td>
<td>44</td>
<td>3/2</td>
<td>-</td>
<td>0.009±0.010</td>
<td>0.15</td>
<td>0.06±0.06</td>
<td>207±23</td>
<td></td>
</tr>
<tr>
<td>1776±6</td>
<td>129±16</td>
<td>5/2</td>
<td>-</td>
<td>0.071±0.008</td>
<td>0.5</td>
<td>0.14±0.02</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>1915</td>
<td>65</td>
<td>5/2</td>
<td>+</td>
<td>0.012±0.008</td>
<td>0.10</td>
<td>0.12±0.08</td>
<td>6±18</td>
<td></td>
</tr>
<tr>
<td>2035</td>
<td>160</td>
<td>7/2</td>
<td>+</td>
<td>0.137±0.050</td>
<td>0.25</td>
<td>0.55±0.20</td>
<td>162±9</td>
<td></td>
</tr>
</tbody>
</table>
Figure Legends

Fig. 1. The differential cross section, $d\sigma/d\Omega$, and the lambda polarization, $P_\Lambda$, in the reaction $K^- + n \rightarrow \Lambda + \pi^-$ in the c.m. energy region 1660 to 1900 MeV. The differential cross section is displayed in the lower portion of each figure, the lambda polarization in the upper portion.

Fig. 2. Coefficients $A_1/A_0$ and $B_1/A_0$ obtained by fitting the angular and polarization distributions in Fig. 1 with the expansion

$$d\sigma/d\Omega = \hat{\kappa} \sum_m A_m P_m (\hat{K} \cdot \hat{\ell})$$

and

$$(d\sigma/d\Omega) \cdot \hat{P} = \hat{\kappa} \sum_m B_m P_m I(\hat{K} \cdot \hat{\ell}).$$

The lower portion of each figure shows $A_1/A_0$, and the upper portion $B_1/A_0$, plotted against c.m. energy. The continuous curves are calculated from solution 1a, with resonant $D_5$ amplitude; the dashed curves correspond to solution 1b, with resonant $F_5$ amplitude.

Fig. 3. Magnitude and phases of the amplitudes which best fit the experimental data in Fig. 1 for the assumption of constant $S_1$, $P_1$, $P_3$, $D_3$ amplitudes and (a) a resonant $D_5$ amplitude (b) a resonant $F_5$ amplitude (c) resonant $D_5$ and $Y_4^*(2030)$ with $J^P = 7/2^+$ or (d) resonant $D_5$, $Y_4^*(2030)$ with $J^P = 7/2^+$, and $Y_4^*(1915)$ with $J^P = 5/2^+$. The resonant amplitude traces a circle counterclockwise as the energy increases; c.m. energies are indicated on the periphery of the circle.
Fig. 1
Fig. 2
Fig. 3
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