Properties of the $\Lambda(1670)\frac{1}{2}^{-}$ Resonance

D. M. Manley,[1] V. V. Abaev,[2] C. E. Allgower,[3,*] V. Bekrenev,[2] W. J. Briscoe,[4] M. Clajus,[5] J. R. Comfort,[6] K. Craig,[6] D. Grosnick,[7] D. Isenhower,[8] N. Knecht,[9] D. D. Koetke,[7] A. A. Kulbardis,[2] N. G. Kozlenko,[2] S. Kruglov,[2] G. Lolos,[9] I. V. Lopatin,[2] R. Manweiler,[7] A. Marušić,[5,†] S. McDonald,[5,‡] B. M. K. Nefkens,[5] J. Olmsted,[1,*] Z. Papandreou,[9] D. C. Peaslee,[10] N. Phaisangittisakul,[5] S. Prakhov,[5] J. W. Price,[5] A. F. Ramirez,[6] M. Sadler,[8] A. Shafi,[4] H. Spinka,[3] T. D. S. Stanislaus,[7] A. Starostin,[5] H. M. Staudenmaier,[11] I. I. Strakovsky,[4] I. Supek,[12] and W. B. Tippens[5,§]

(Crystal Ball Collaboration)

[1] *Kent State University, Kent, Ohio 44242-0001*
[2] *Petersburg Nuclear Physics Institute, Gatchina, Russia 188350*
[3] *Argonne National Laboratory, Argonne, Illinois 60439-4815*
[4] *The George Washington University, Washington, D.C. 20052-0001*
[5] *University of California Los Angeles, Los Angeles, California 90095-1547*
[6] *Arizona State University, Tempe, Arizona 85287-1504*
[7] *Valparaiso University, Valparaiso, Indiana 46383-6493*
[8] *Abilene Christian University, Abilene, Texas 79699-7963*
[9] *University of Regina, Saskatchewan, Canada S4S OA2*
[10] *University of Maryland, College Park, Maryland 20742-4111*
[11] *Universität Karlsruhe, Karlsruhe, Germany 76128*
[12] *Rudjer Bošković Institute, Zagreb, Croatia 10002*

(Received 13 August 2001; published 14 December 2001)

Recently the Crystal Ball Collaboration measured precise new data for the near-threshold reaction $K^- p \to \eta\Lambda$, which is dominated by formation of the $\Lambda(1670)\frac{1}{2}^{-}$. In this Letter, we present results of a unitary, multichannel analysis that incorporates the new Crystal Ball data. For our preferred fit, we obtain mass $M = 1673 \pm 2$ MeV, width $\Gamma = 23 \pm 6$ MeV, and elasticity $x = 0.37 \pm 0.07$. This elasticity is significantly larger than previously recognized. Resonance parameters of our preferred fit are in striking agreement with the quark-model predictions of Koniuk and Isgur.

DOI: 10.1103/PhysRevLett.88.012002 PACS numbers: 11.80.Gw, 12.39.Jh, 13.30.Eg, 13.75.Jz

In 1965, Berley *et al.* [1] reported a sharp peak in the near-threshold cross section for $K^- p \to \eta\Lambda$. Furthermore, the angular distribution of the η's, albeit measured with low precision, was consistent with isotropy. These observations were consistent with the interpretation that the peak arises from a narrow $\frac{1}{2}^{-}$ resonance, which is now known as the $\Lambda(1670)$. It is generally accepted today that this state is the SU(3) octet partner of the $N(1535)$, which dominates the near-threshold reactions $\pi^- p \to \eta n$ and $\gamma p \to \eta p$. The $\Lambda(1670)$ and $N(1535)$ are of special interest because they are two of only three baryon resonances known to have appreciable decays involving the η meson [2]. Much experimental [3–6] and theoretical [7–12] effort has been devoted recently to determining the resonance parameters of $N(1535)$ more accurately; however, until recently, there has been no opportunity to make similar improvements for the $\Lambda(1670)$. That situation changed in 1998 when we measured precise cross-section data for the near-threshold reaction $K^- p \to \eta\Lambda$ using the Crystal Ball multiphoton spectrometer at the Brookhaven National Laboratory AGS [13].

In this Letter, we apply a unitary multichannel parametrization to fit the total cross section, $\sigma_{\rm tot}(K^- p \to \eta\Lambda)$, as well as several $I = 0$ S-wave $\overline{K}N$ partial-wave amplitudes. The parametrization was developed by one of us (D. M. M.) and has been applied successfully to describe πN elastic and inelastic scattering, including pion photoproduction [14]. A brief summary of the method is presented here.

We begin with a generalization of the well-known multichannel Breit-Wigner representation for T-matrix amplitudes. The dimensionless T matrix is related to the unitary partial-wave S matrix according to $S = 1 + 2iT$. In our approach, background contributions were included empirically by writing the S matrix as $S = B^{\rm T}RB$, where B is a unitary background matrix (not generally symmetric), $B^{\rm T}$ is the transpose of B, and R is the symmetric S matrix in the absence of any background. Background couplings having the proper threshold behavior (analogous to direct resonance couplings) may be introduced in each channel. The resonant part R was constructed from a novel K-matrix approach. We may write $R = 1 + 2iK(1 - iK)^{-1}$. For n resonances, the elements of K at c.m. energy W may be written as

$$K_{ij} = \sum_{r=1}^{n} g_{ij}^{r}(W)\,\frac{\Gamma_r(W)/2}{M_r(W) - W}\,. \tag{1}$$

Here $g_{ij}^{r}(W) = g_i^r(W)g_j^r(W)$ are elements of a matrix with unit trace. The energy dependence of $\Gamma_r(W)$ and $M_r(W)$ was developed in such a way that the Breit-Wigner parameters of the corresponding T matrix can be easily identified. In our approach, resonance poles may be extracted, but dispersion relations are not incorporated explicitly. Further details about our method may be found in Ref. [15].

Most of the partial-wave analyses (PWAs) performed in the early 1970s were based on simple energy-dependent parametrizations of the partial-wave amplitudes and were confined to rather narrow energy ranges, normally that of a single bubble-chamber experiment. One exception was the 1972 energy-independent coupled-channel PWA (LANGBEIN 72) of Langbein and Wagner [16]. These authors obtained single-energy solutions over the c.m. energy range 1536 to 1898 MeV. For the GOPAL 1977 PWA [17], conventional energy-dependent solutions were first obtained for each of the three channels $\overline{K}N$, $\pi\Lambda$, and $\pi\Sigma$ in the c.m. energy range 1480 to 2170 MeV. The three separate fits were then considered together to find solutions with consistent parameters for the resonances in each channel. This PWA was updated for $\overline{K}N \to \overline{K}N$ in 1980 (GOPAL 80) [18]. Another important PWA (MARTIN 77) was that of Martin and Pidcock [19]. This multichannel energy-dependent PWA was performed over the c.m. energy range 1540 to 2000 MeV using a traditional K-matrix parametrization to impose unitarity. The single-channel PWA ALSTON 78 is also worth mentioning. This was an energy-dependent PWA [20] of $\overline{K}N \to \overline{K}N$ covering the c.m. energy range 1500 to 1940 MeV. Cusp effects at the $\eta\Lambda$ and $\eta\Sigma$ thresholds were included by adding a square-root singularity in the energy dependence of the total widths of the appropriate resonances. The most recent energy-dependent PWA, KOISO 85 [21], was performed over the restricted c.m. energy range 1606 to 1741 MeV.

In the present work, we carried out a multichannel fit over the c.m. energy range 1500 to 1900 MeV that included precise near-threshold data [13] obtained with the Crystal Ball for $\sigma_{\rm tot}(K^- p \to \eta\Lambda)$. The reader is directed to Ref. [13] for details of the experiment. Older, less precise data for $\sigma_{\rm tot}$ were not included in our fit. We made the reasonable assumption that only the S-wave amplitude makes a significant contribution to the total cross section [22]. This assumption is supported by a preliminary PWA of our measured differential cross section and polarization data. In this approximation, we may write $\sigma_{\rm tot}(K^- p \to \eta\Lambda) = 2\pi k^{-2}|T|^2$, where k the incident momentum in the c.m. frame and T is the S-wave amplitude for $\overline{K}N \to \eta\Lambda$. Prior PWAs show that the $\overline{K}N \to \overline{K}N$ and $\overline{K}N \to \pi\Sigma$ S_{01} amplitudes require a large nonresonant background in the vicinity of the $\Lambda(1670)$. Most analyses also require a broad $\Lambda(1800)$ resonance in order to fit data up to 1900 MeV. To accommodate these structures and constrain the $\overline{K}N \to \eta\Lambda$ amplitude, we included the $\overline{K}N \to \overline{K}N$ and $\overline{K}N \to \pi\Sigma$ S_{01} amplitudes from the GOPAL 77 solution in our fit. We performed an alternative fit using the $\overline{K}N \to \overline{K}N$ amplitude from the ALSTON 78 solution that gave similar values for the $\Lambda(1670)$ resonance parameters. Our preferred fit used the GOPAL 77 elastic amplitude because it gave better overall agreement with the $\sigma_{\rm tot}(K^- p \to \eta\Lambda)$ data. As a further constraint, we included the $\overline{K}N \to \pi\Sigma(1385)$ $SD01$ amplitude obtained from the CAMERON 78 PWA [23] of data in the c.m. energy range 1775 to 2170 MeV. To satisfy unitarity and to account for flux into all other final states, our fit also included two quasi-two-body channels for a total of six channels altogether. Nonresonant background was included in all six channels. The two added channels were $(\pi\pi)_S\Lambda$ and $(\pi\pi)_P\Sigma$. We assigned an uncertainty of ± 0.05 to the real and imaginary parts of the input amplitudes. This uncertainty reflects the typical difference obtained from different energy-dependent PWAs. Our best fit obtained an overall χ^2 per degree of freedom of 1.2 and included the broad $\Lambda(1800)$, which we discuss briefly below. The $\Lambda(1405)$, which has a width of about 50 MeV, was outside the energy range of our fit.

Figure 1 shows results of the six-channel fit for our $\sigma_{\rm tot}(K^- p \to \eta\Lambda)$ data [13]. Figures 2 and 3, respectively, show the corresponding results obtained in a simultaneous fit for the S_{01} $\overline{K}N$ elastic and $\overline{K}N \to \pi\Sigma$ partial-wave amplitudes. Solid circles mark the fitted resonance energies corresponding to the $\Lambda(1670)$ and $\Lambda(1800)$. The $\eta\Lambda$ cusp just below 1663 MeV is clearly visible in our fit. Table I summarizes our results for the resonance parameters of the $\Lambda(1670)$. Quoted uncertainties in all resonance parameters were calculated using the full error matrix to propagate the uncertainties in the fitted input data. The fitted mass, $M = 1673 \pm 2$ MeV, is consistent with the most recent results listed in the *Review of Particle Physics* (RPP) [24]. Table II compares our results

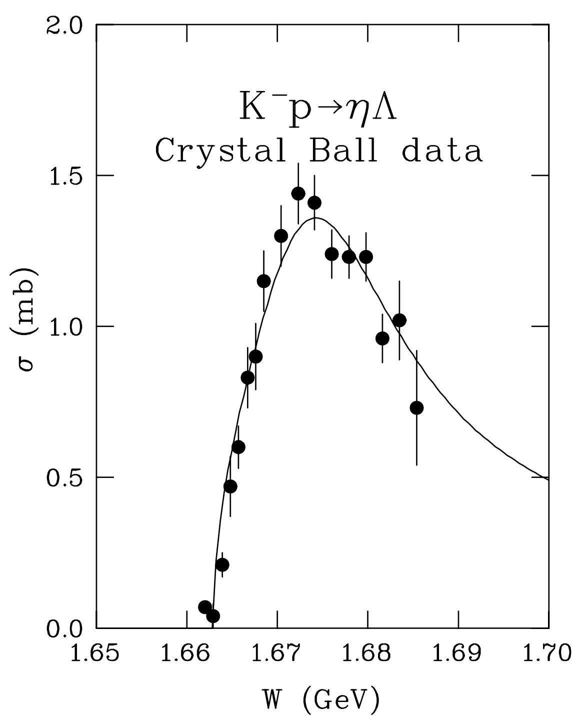

FIG. 1. Total cross section for the $K^- p \to \eta\Lambda$ as measured by the Crystal Ball Collaboration. The curve shows the result of our multichannel fit.

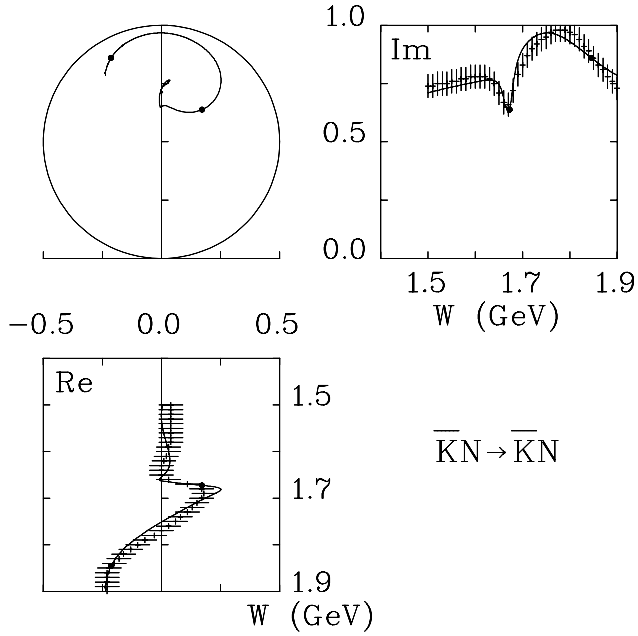

FIG. 2. Argand amplitude for the $\overline{K}N \to \overline{K}N$ S_{01} partial wave. The curve shows the result of our multichannel fit. Solid dots mark the energies for the $\Lambda(1670)$ and $\Lambda(1800)$. The data are from the energy-dependent GOPAL 77 analysis (see text).

with those from representative prior analyses. The total width, $\Gamma = 23 \pm 6$ MeV, is consistent with the values of the GOPAL 80 and ALSTON 78 solutions. For the GOPAL 77 solution [17], the width of 45 ± 10 MeV was determined from fitting the $\overline{K}N \to \pi\Sigma$ data where pure

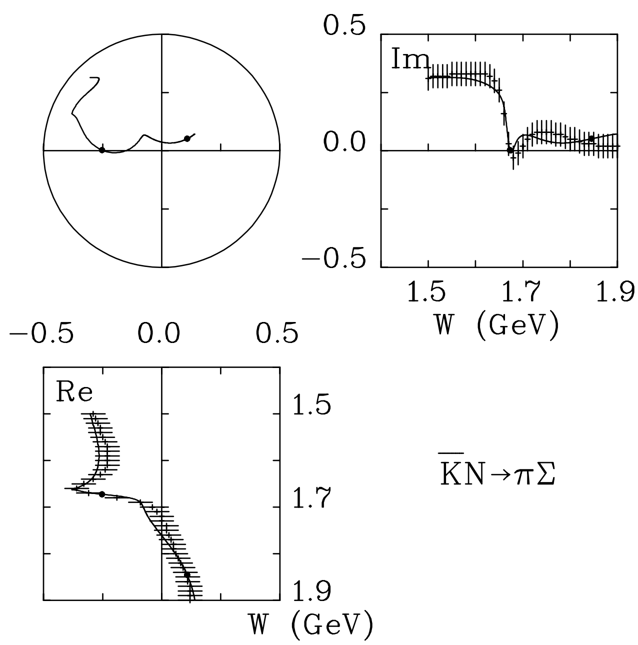

FIG. 3. Argand amplitude for the $\overline{K}N \to \pi\Sigma$ S_{01} partial wave. The curve shows the result of our multichannel fit. Solid dots mark the energies for the $\Lambda(1670)$ and $\Lambda(1800)$. The data are from the energy-dependent GOPAL 77 analysis (see text).

TABLE I. Resonance parameters for the $\Lambda(1670)$ as determined from our multichannel fit. The fitted Breit-Wigner mass and total width have the values $M = 1673 \pm 2$ MeV and $\Gamma = 23 \pm 6$ MeV, respectively. The corresponding pole position is $(1671 - i11)$ MeV. In the columns below, Γ_i is the partial width for the ith decay channel evaluated at the resonance energy, x_i is the corresponding branching fraction, $x = 0.37 \pm 0.07$ is the elasticity, and t is the amplitude at resonance excluding contributions from nonresonant background.

Channel	Γ_i (MeV)	$x_i = \Gamma_i/\Gamma$ (%)	$t = \sqrt{xx_i}$
$\overline{K}N$	8.5 ± 2.6	37.3 ± 6.8	0.37 ± 0.07
$\eta\Lambda$	3.6 ± 1.4	15.7 ± 5.5	0.24 ± 0.04
$\pi\Sigma$	8.8 ± 3.2	38.6 ± 7.9	-0.38 ± 0.03
$\pi\Sigma(1385)$	1.7 ± 1.5	7.6 ± 6.0	-0.17 ± 0.06
$\pi\pi\Lambda$	<1	<4	0.05 ± 0.11
$\pi\pi\Sigma$	<1	<1	0.00 ± 0.06

I-spin data were available. The $\overline{K}N \to \overline{K}N$ data preferred a narrower width ($\sim$25 MeV), but in their final fits, Gopal *et al.* held the mass and width fixed at the values from their fit of the $\overline{K}N \to \pi\Sigma$ data. It is clear from the Argand diagrams in Figs. 2 and 3 that the $\overline{K}N \to \overline{K}N$ and $\overline{K}N \to \pi\Sigma$ amplitudes have very large backgrounds in the vicinity of $\Lambda(1670)$; therefore, analyses that included only these isospin-mixed reactions may very well give unreliable results for the S_{01} resonance parameters. On the other hand, our precise cross-section data for the pure $I = 0$ $K^-p \to \eta\Lambda$ reaction has a narrow peak that clearly requires a narrow width for $\Lambda(1670)$.

Our value for the $\Lambda(1670)$ elasticity, $x = 0.37 \pm 0.07$, is about twice as large as those listed in the RPP as being from the GOPAL 80 and ALSTON 78 solutions. Although the large backgrounds present in the $\overline{K}N \to \overline{K}N$ and $\overline{K}N \to \pi\Sigma$ S_{01} amplitudes can be expected to make it difficult to determine resonance parameters such as the elasticity, it is worth noting that the value for the "elasticity" listed as 0.17 ± 0.03 for the ALSTON 78 solution is actually the diameter of the circle in the Argand diagram for the elastic amplitude. According to Alston-Garnjost *et al.* [20], this value should be more properly identified as $\eta_B x$, where $\eta_B < 1$ is the absorption parameter for the (large) background.

Our results for the inelastic amplitudes at resonance, $t = \sqrt{xx'}$, excluding contributions from nonresonant background, are in good agreement with prior analyses. For

TABLE II. Comparison of the mass M, total width Γ, and elasticity x for the $\Lambda(1670)$ with results of selected prior analyses.

M (MeV)	Γ (MeV)	x	Analysis
1673 ± 2	23 ± 6	0.37 ± 0.07	This work
1667 ± 5	29 ± 5	0.18 ± 0.03	GOPAL 80
1671 ± 3	29 ± 5	0.17 ± 0.03	ALSTON 78
1670 ± 5	45 ± 10	0.20 ± 0.03	GOPAL 77
1640 ± 40	45 ± 20	0.35 ± 0.06	LANGBEIN 72

example, we obtain $t = 0.24 \pm 0.04$ for the $\eta\Lambda$ channel, which agrees with the value 0.24 obtained by Abaev and Nefkens [25] in a constrained fit to older $K^- p \to \eta\Lambda$ data. For the $\pi\Sigma$ channel, our value $t = -0.38 \pm 0.03$ is in fair agreement with the values -0.26 ± 0.02 and -0.31 ± 0.03 from the KOISO 85 and GOPAL 77 solutions, respectively. Finally, for the $\pi\Sigma(1385)$ channel, our value $t = -0.17 \pm 0.06$ is in excellent agreement with the value -0.18 ± 0.05 obtained from an energy-dependent PWA of $\overline{K}N \to \pi\Sigma(1385)$ by Prevost *et al.* [26].

By including the GOPAL 77 (ALSTON 78) elastic amplitude in our fit, the broad $\Lambda(1800)$ resonance is found to have mass $M = 1845 \pm 10$ MeV (1804 ± 5 MeV), width $\Gamma = 518 \pm 84$ MeV (395 ± 47 MeV), and elasticity $x = 0.24 \pm 0.10$ (0.19 ± 0.09). The corresponding pole is at $(1728 - i184)$ MeV [$(1706 \pm i108)$ MeV]. For both fits, the inelastic couplings of $\Lambda(1800)$ were poorly determined. It is possible that we might obtain a more precise determination of the $\Lambda(1800)$ resonance parameters by increasing the maximum energy for our fit.

It is of interest to compare our results for the $\Lambda(1670)$ with nonrelativistic quark-model predictions. Capstick and Roberts [27] recently made an extensive review of quark models of baryon masses and decays; however, we are unaware of any *recent* calculations for *hyperon* decays. Koniuk and Isgur [28] calculate "decay amplitudes," which equal $S_{\rm in} S_{\rm out} \sqrt{\Gamma_{\rm out}}$, where $S_{\rm in(out)}$ is the sign of the ingoing (outgoing) amplitude and $\Gamma_{\rm out}$ is the partial width of the outgoing decay channel. For $\overline{K}N$, they predict the value 3.3, compared with our fitted value, 2.9 ± 0.4; for $\pi\Sigma$, they predict the value -3.2, compared with our fitted value, -3.0 ± 0.5; for $\eta\Lambda$, they predict the value $+2.2$, compared with our fitted value, 1.9 ± 0.3; finally for $\pi\Sigma(1385)$, they predict the value -1.2, compared with our fitted value, -1.3 ± 0.5. All values are in MeV$^{1/2}$. Our agreement with the predictions is remarkable.

In summary, precise modern data for $\sigma_{\rm tot}(K^- p \to \eta\Lambda)$ were used for the first time in a unitary six-channel analysis to determine resonance parameters for the $\Lambda(1670)$. The resonance was found to be narrower ($\Gamma = 23 \pm 6$ MeV) with a larger elasticity than previously recognized. Our results for the resonant inelastic amplitudes, $\sqrt{xx'}$, agree well with prior analyses, and, overall, our resonance parameters for the $\Lambda(1670)$ are in excellent agreement with the quark-model predictions of Koniuk and Isgur.

We wish to thank Anders Gårdestig for his PWA calculations. This work was supported in part by DOE, NSF, NSERC of Canada, and the Russian Ministry of Science and Technology. The assistance of BNL is also gratefully acknowledged.

*Present address: Indiana University Cyclotron Facility, 2401 Milo B. Sampson Lane, Bloomington, IN 47405.
†Present address: Collider-Accelerator Department, Brookhaven National Laboratory, Upton, NY 11973.
‡Present address: TRIUMF, 4004 Wesbrook Mall, Vancouver, British Columbia, Canada V6T 2A3.
§Present address: Nuclear Physics Division, Department of Energy, 19901 Germantown Road, Germantown, MD 20874-1290.

[1] D. Berley *et al.,* Phys. Rev. Lett. **15**, 641 (1965).
[2] The only other known baryon resonance with a large η branch is the $\Sigma(1750)\frac{1}{2}^-$.
[3] S. A. Dytman *et al.,* Phys. Rev. C **51**, 2710 (1995).
[4] J. W. Price *et al.,* Phys. Rev. C **51**, R2283 (1995).
[5] B. Krusche *et al.,* Phys. Rev. Lett. **74**, 3736 (1995).
[6] B. Krusche *et al.,* Phys. Lett. B **358**, 40 (1995); **376**, 331(E) (1996).
[7] Ch. Sauermann, B. L. Friman, and W. Nörenberg, Phys. Lett. B **341**, 261 (1995).
[8] G. Knöchlein, D. Dreschel, and L. Tiator, Z. Phys. A **352**, 327 (1995).
[9] Z. Li, Phys. Rev. D **52**, 4961 (1995).
[10] N. C. Mukhopadhyay, J.-F. Zhang, and M. Benmerrouche, Phys. Lett. B **364**, 1 (1995).
[11] Z. Li and R. Workman, Phys. Rev. C **53**, R549 (1996).
[12] B. Krusche *et al.,* Phys. Lett. B **397**, 171 (1997).
[13] A. Starostin *et al.,* Phys. Rev. C **64**, 055205 (2001).
[14] D. M. Manley, Few-Body Syst. Suppl. **11**, 104 (1999); (unpublished).
[15] M. M. Niboh, Ph.D. dissertation, Kent State University, 1997.
[16] W. Langbein and F. Wagner, Nucl. Phys. **B47**, 477 (1972).
[17] G. P. Gopal *et al.,* Nucl. Phys. **B119**, 362 (1977).
[18] G. P. Gopal *et al.,* in *Proceedings of the IVth International Conference on Baryon Resonances, Toronto, 1980,* edited by N. Isgur (University of Toronto, Toronto, 1980), p. 159.
[19] B. R. Martin and M. K. Pidcock, Nucl. Phys. **B126**, 266 (1977); **B126**, 285 (1977); **B126**, 349 (1977).
[20] M. Alston-Garnjost *et al.,* Phys. Rev. D **18**, 182 (1978).
[21] H. Koiso *et al.,* Nucl. Phys. **A433**, 619 (1985).
[22] Our $d\sigma/d\Omega$ data for $K^- p \to \eta\Lambda$ require higher partial waves, but only S waves contribute significantly to $\sigma_{\rm tot}$ near threshold.
[23] W. Cameron *et al.,* Nucl. Phys. **B143**, 189 (1978).
[24] Particle Data Group, D. E. Groom *et al.,* Eur. Phys. J. C **15**, 1 (2000).
[25] V. V. Abaev and B. M. K. Nefkens, Phys. Rev. C **53**, 385 (1996).
[26] J. Prevost *et al.,* Nucl. Phys. **B69**, 246 (1974).
[27] S. Capstick and W. Roberts, Prog. Part. Nucl. Phys. Suppl. 2 **45**, S241 (2000).
[28] R. Koniuk and N. Isgur, Phys. Rev. D **21**, 1868 (1980).