Scrying new physics with the Crystal Ball

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A program in baryon spectroscopy and meson decays with the Crystal Ball Detector is underway at the Brookhaven National Laboratory. A vast amount of high-quality data are being obtained on the formation and decays of N^*, Δ, Λ, and Σ resonances. Threshold η production patterns are very similar in $\pi^- p$ and $K^- p$ interactions. Comprehensive $2\pi^0$ data are best described by sequential decays through intermediate resonances. Precision studies of eta-meson decays are setting stringent challenges to theoretical descriptions.

1 Introduction

The concept of a Crystal Ball goes back to the days of Nostradamus. He would take a bowl of water, place it on a stand and stare at the reflection of some light from its surface. After some time, he would utter a rhyme, understood to be either about an upcoming event or an interpretation of a past event. With many of them deemed to be valid or successful, he won great fame for his ability to discern ("scry") the future. Through a comprehensive program in studying the formation and decays of baryon resonances and precision measurements of meson decays, the Crystal Ball Collaboration[1] is also seeking to *discern* new understandings of subatomic structure and interactions.

The SLAC Crystal Ball (CB) spectrometer was moved to Brookhaven National Laboratory (BNL) in 1995. After an engineering run in 1997, extensive data were obtained over four months of running in 1998 for a wide variety of reactions and decays. Some of the reaction channels and decays are listed in Table I. Neutral channels, whose end result is a neutron plus one or more photons, are produced. In this regard, the CB program complements the studies at the Jefferson Laboratory and elsewhere, at which charged channels are studied.

Table I. Decay Channels.

$\pi^- p$	$\rightarrow$	$\gamma\, n$
		$\pi^0\, n$
		$\pi^0\, \pi^0\, n$
		$\eta\, n$
$K^- p$	$\rightarrow$	$\pi^0\, \Lambda$
		$\pi^0\, \pi^0\, \Lambda$
		$\eta\, \Lambda$
		$\pi^0\, \Sigma^0$
		$\pi^0\, \pi^0\, \Sigma^0$
π^0	$\rightarrow$	$\gamma\, \gamma$
η	$\rightarrow$	$\gamma\, \gamma$
Λ	$\rightarrow$	$\pi^0\, n$
Σ	$\rightarrow$	$\gamma\, \Lambda$

Several results have already been published [1–5], and many more are yet to come. Some of these will be discussed below. The others are described briefly here.

- Prior to our experiments, very little information was known previously about the interaction of neutrons in our energy range with NaI(Tl). By using kinematic constraints of the two-body $\pi^- p \rightarrow \pi^0 n$ reaction, we were able to map out the response as a function of energy. Detection efficiencies reach as much as 35-40%. Special tuning of the Monte Carlo GEANT321 code was necessary to reproduce the behavior [3].
- Some data were obtained for $2\pi^0$ production from nuclear targets. Interest in this process was stimulated by results from the CHAOS group at TRIUMF for the $(\pi^+, \pi^-\pi^+)$ reaction which

[1]The Crystal Ball Collaboration consists of members from Abilene Christian University, Argonne National Laboratory, Arizona State University, University of California Los Angeles, University of Colorado, The George Washington University, Universität Karlsruhe, Kent State University, University of Maryland, Pertersburg Nuclear Physics Institute, University of Regina, Rudjer Bošković Institute, and Valparaiso University.

were interpreted that "nuclear matter strongly modifies the $\pi\pi$ interaction in the $J=I=0$ channel" [6]. Our results for an analogue $2\pi^0$ channel do not have a sharp peak near the 2π threshold as seen in the CHAOS data [2]. While there appears to be a shift of the invariant $2\pi^0$ mass distribution towards threshold with increasing nuclear mass, recent analyses suggest that it actually results from a supression of strength at high invariant mass due to increasing absorption of the $\Delta(1232)$ with higher nuclear mass.

A review of the N^* and Δ resonances [7] reveals substantial uncertainties in their listed properties. Considering the 4-star resonances alone, the masses are often specified only within 50 MeV and are sometimes uncertain by as much as 100 MeV. Similarly, the widths are typically poorly known and are often uncertain by as much as 150-200 MeV. The decay widths to particular channels are even less well known. The situation is worse for the hyperons. Some properties of Λ and Σ resonances are listed in Table II. Most of the data are quite old and typically of poor statistics.

Table II: Properties of Λ and Σ resonances.

Resonance	$2J^\pi$	PDG	P_{K^-} (MeV/c)	Mass (MeV)	Width (MeV)
$\Lambda(1405)$	1^-	****	—	1406±4	50±2
$\Lambda(1520)$	3^-	****	390	1520±1	16±1
$\Lambda(1600)$	1^+	***	580	1560-1700	50-250
$\Lambda(1670)$	1^-	****	740	1660-1680	25-50
$\Lambda(1690)$	3^-	****	780	1685-1695	50-70
$\Sigma(1385)$	3^+	****	—	1384±1	36±5
$\Sigma(1480)$	??	*	280	~1480	~50
$\Sigma(1560)$	??	**	490	~1560	~50
$\Sigma(1580)$	3^-	**	540	~1580	~15
$\Sigma(1620)$	1^-	**	630	~1620	20-85
$\Sigma(1660)$	1^+	***	720	1630-1690	40-200
$\Sigma(1670)$	3^-	****	740	1665-1685	40-80
$\Sigma(1690)$	??	**	780	~1690	30-150

2 K^-p reactions

Our CB program in experiment E914 is already providing new data with much improved precision for the first time in 20 years. A nice feature of the CB program is the ability to select states of pure isospin, as shown in Table III. I will describe and illustrate only a small portion of the data that we have.

Table III. K^-p selectivity.

$\left.\begin{array}{l}K^-p\to\eta\Lambda\\ K^-p\to\pi^0\Sigma^0\end{array}\right\}$	Pure $I=0$	Selects Λ^*
$K^-p\to\pi^0\Lambda$	Pure $I=1$	Selects Σ^*
$K^-p\to\overline{K^0}n$	Mixed $I=0,1$	

2.1 $K^-p\to\eta\Lambda$

Eta mesons are cleanly identified in the CB through their $\gamma\gamma$ and other decay channels. The total and differential cross sections for the $K^-p\to\eta\Lambda$ reaction near threshold are dominated by formation of the $\Lambda(1670)\frac{1}{2}^-$ resonance. There are many similarities between this reaction and the $\pi^-p\to\eta n$ reaction near threshold, which is dominated by the $N(1535)\frac{1}{2}^-$ resonance. These include a steep rise in the total cross section with similar values of the dependence on η momentum, peaking slightly above the threshold (see Fig. 1). The angular distributions are consistent with S-wave dominance, but with a small D-wave contribution that provides a slight bowl shape. The data support the view that the $N(1535)$ and $\Lambda(1670)$ states belong to the same SU(3) octet. A full paper on this reaction has been published [5]. A description of a unitary, multichannel analysis for data in the region of the $\Lambda(1670)$ state is given elsewhere in these proceedings [8].

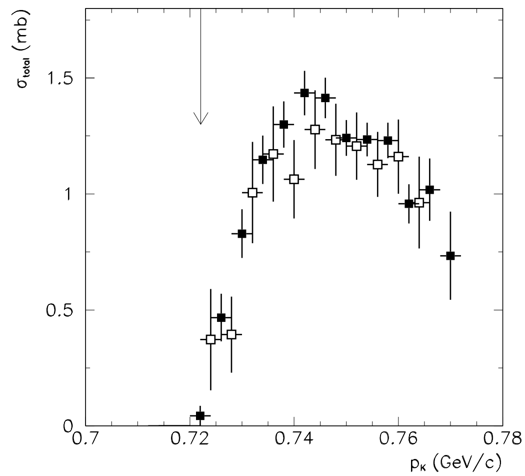

Figure 1: Total cross sections for the $K^-p \to \eta\Lambda$ reaction. The solid (open) squares are for the $\eta \to \gamma\gamma$ ($3\pi^0$) decay mode. The arrow marks the threshold.

2.2 Other K^-p reactions

Differential cross sections and Λ polarizations were obtained at 18 momenta for the $K^-p \to \pi^0\Lambda$, $K^-p \to \overline{K^0}n$ and $K^-p \to \pi^0\Sigma$ reactions in the momentum range between 492 and 761 MeV/c [9]. Some of the data for 640 MeV/c are shown in Fig. 2. The coefficients A_n/A_0 for expansion in Legendre polynomials

$$\frac{d\sigma}{d\Omega} = \lambda\!\!\!^{-2} \sum_{n=0}^{n_{\max}} A_n P_n(\cos\theta) \tag{1}$$

were also obtained. Terms through $n=3$ are needed, while the $n=4$ terms are typically consistent with zero. From the polarization $P(\theta)$ data, the coefficients B_n/B_0 of the expansion

$$P(\theta)\cdot\frac{d\sigma}{d\Omega} = \lambda\!\!\!^{-2} \sum_{n=0}^{n_{\max}} B_n P_n^1(\cos\theta)\ , \tag{2}$$

where P_n^1 are the associated Legendre polynomials, could also be obtained. They are typically small, although the B_2/B_0 coefficients tend to become slightly negative at the higher momenta.

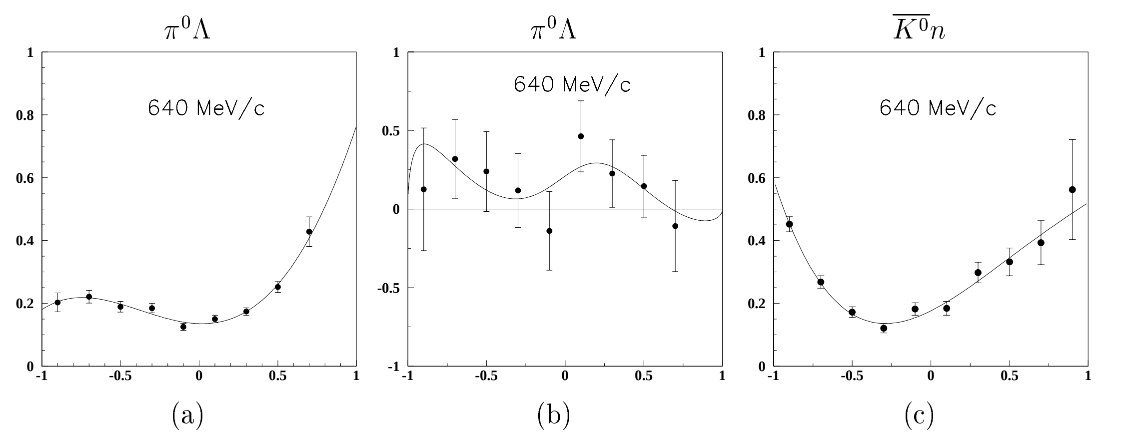

Figure 2: Cross sections (mb/sr) or polarizations for $K^-p \to \pi^0\Lambda$ reaction (left two figures), and $K^-p \to \overline{K^0}n$ reaction (right figure). The curves were obtained from fits with Eqs. (1) and (2).

As noted in Table II, the existence of the $\Sigma(1580)$ resonance is doubtful. Because quark models are unable to produce such a state at low energies, confirmation of the resonance would be a major challenge to them. The results of our analysis suggest that the $\Sigma(1580)$ is probably not needed. A full partial-wave analysis, including the new CB data, will be done to examine this issue in more detail.

3 Double π^0 production

Considerable attention has been given to a study of the $\pi^- p \to \pi^0\pi^0 n$ reaction. We are interested in the mechanism for $2\pi^0$ production as well as resonance structures in the $\pi^0\pi^0$ and $\pi^0 n$ invariant masses. An important question is the degree to which the two π^0's are formed as a correlated pair (*e.g.*, the elusive and controversial $f_0(400-1200)$ or "σ" particle), as distinguished from sequential π^0 decay through intermediate resonances (*e.g.*, $N^* \to \Delta(1232)\pi^0 \to n\pi^0\pi^0$). If formed by the (virtual) process $\pi_v^+\pi^- \to \pi^0\pi^0$, one can obtain important information on the isoscalar $\pi\pi$ scattering length a_0^0. A clearly evident resonance structure would give strong support to the existence of the σ particle. Recent photo-production data have provided evidence for a strong sequential process from the $D_{13}(1520)$ resonance through the $\Delta(1232)$ [10,11]. On the other hand, a broad peak with the characteristics of a σ particle has been reported from the $\pi^- p \to \pi^0\pi^0 n$ reaction at 9 GeV [12].

Data were obtained for 19 beam momenta in the range 0.30–0.75 GeV/c. This study is the most thorough ever of $2\pi^0$ production in $\pi^- p$ interactions. The Dalitz plots (at least above 0.350 GeV/c) do not have phase-space distributions, but rather show strong enhancements of the yields at high $2\pi^0$ invariant mass, typically also with a small peak at low invariant mass. See Fig. 3. In the $\pi^0 n$ projection, the enhancements are also near the mass of the $\Delta(1232)$.

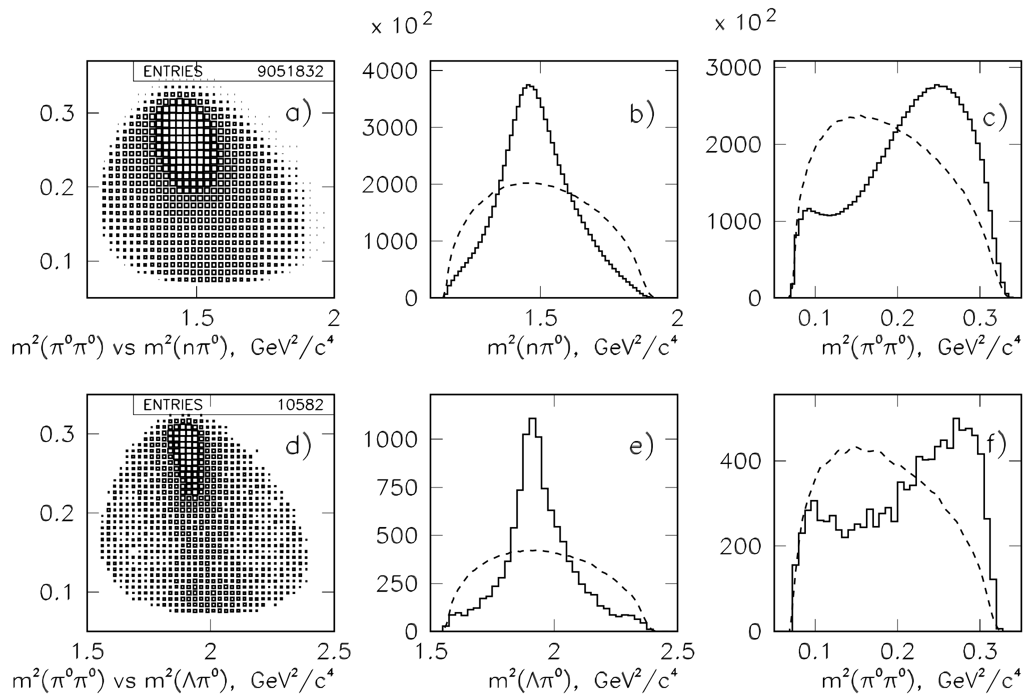

Figure 3: Dalitz plot and projections for the $\pi^- p \to \pi^0\pi^0 n$ reaction at 720 MeV/c (upper row), and the $K^- p \to \pi^0\pi^0\Lambda$ reaction at 750 MeV/c (lower row). The phase-space distributions (dashed lines) are shown on the projections.

The enhancement at high $m^2(\pi^0\pi^0)$ is in the region expected for the σ meson, which is cut off by our kinematics. On the other hand, the enhancement in $m^2(\pi^0 n)$ is near the location of the $\Delta(1232)$

(more accurately, the maximum of the $\pi^- p$ total cross section). One of the signatures for the σ is that the decay into two π^0's must be isotropic in its rest frame. As shown in the upper half of Fig. 4, neither the θ nor the ϕ distribution, in the Gottfried-Jackson (G-J) frame, is isotropic. (The ϕ angle here is also known as the Treiman-Yang angle [14].) We can also examine the hypothesis that the σ is formed via one-pion exchange (OPE). In that case, the four-momentum transfer is expected to peak near $-t \sim 1 \cdot m_\pi^2$ [13,14]. We find in the lower part of Fig. 4 that $-t$ actually peaks near 0.32 $(\mathrm{GeV}/c)^2$, or about $20 m_\pi^2$. The implications are that OPE contributes very weakly to these data, and that there is very little if any production of the σ.

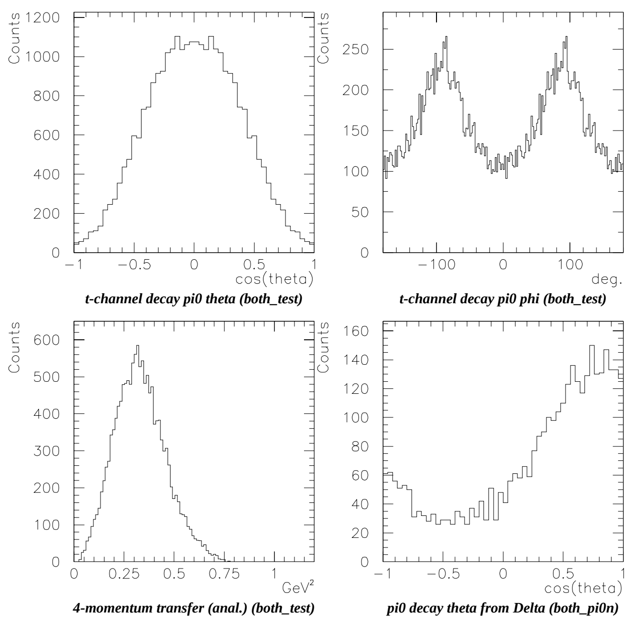

Figure 4: Distributions of double-π^0 production and decay. $\cos\theta$ (upper left) and ϕ (upper right) distributions in the double π^0 rest frame; t distribution of double-π^0 production (lower left); θ distribution of π^0 from a Δ^0.

The Dalitz plots and the projections show a very stable and consistent pattern as a function of energy. For momenta below about 650 MeV/c, the peak of the $m^2(\pi^0 n)$ distributions shifts to lower values, moving down to about 1.2 $(\mathrm{GeV}/c)^2$. For the $m^2(\pi^0\pi^0)$ distributions, the small peak at low m^2 vanishs below about 0.55 $(\mathrm{GeV}/c)^2$. We understand these behaviors as resulting from kinematics: as the incident momentum decreases, there is less energy for decays through the upper side of the Δ resonance. The data are thus consistent with the sequential π^0 decay of a nucleon resonance through the $\Delta(1232)$ over the entire momentum range of this experiment. The main resonances in this region are the $N(1440)\frac{1}{2}^+$ and $N(1520)\frac{3}{2}^-$, and so this reaction will help to map out the Roper.

The data were also examined for the reaction $\pi^- p \to \Delta\pi^0$, followed by π^0 decay of the Δ (which is not kinematically distinguishable from the sequential decay of a resonance). Events were selected by requiring that one π^0 and a neutron have an invariant mass within ± 60 MeV of the $\Delta(1232)$, while that for the other combination was more than 60 MeV away. The θ distribution of the π^0 decay of the Δ, which is the angular correlation of the two π^0's from the reaction, is shown in the last portion of Fig. 4. A Monte Carlo simulation of the sequential process, with an empirically determined angular correlation very similar to that in Fig. 4, produced a Dalitz plot almost indistinguishable from that shown in Fig. 3. Analysis of data for the $K^- p \to \pi^0\pi^0\Lambda$ reaction reveals very similar patterns to those of the $\pi^- p$ reaction, as shown in the lower part of Fig. 3. In this case, the decay $\Lambda^* \to \Sigma(1385)\pi^0 \to \Lambda(1116)\pi^0\pi^0$ is flavor symmetric with the N^* decay process. The $\Lambda(1600)\frac{1}{2}^+$ then has a role analogous to that of the $N(1440)\frac{1}{2}^+$. It appears that σ production from baryon resonances is quite small.

4 Decays of the η meson

The decays of the η meson are especially interesting because they allow us to explore the limits of basic symmetries such as C and CP invariance, as well as tests of chiral-perturbation (χPT) expansions and other models. I shall briefly describe some results, where full details are in recent publications [1,4]. Analyses of several other decay modes, including $\eta \to \pi^0\gamma\gamma$, $3\pi^0\gamma$, and 3γ, are nearing completion.

- The first determination was made of the upper limit for the branching ratio of the CP-forbidden decay $\eta \to 4\pi^0$. At the 90% confidence level, we obtained $\mathcal{B} \leq 6.9 \times 10^{-7}$. After making some theoretical adjustments for the very small available phase space, we estimate that this value provides about a 2% limit on CP violation in quark-family-conserving interactions.

- A precision determination was made for the quadratic slope parameter for the $\eta \to 3\pi^0$ decay. Calculations in Chiral Perturbation Theory to order $\mathcal{O}(p^2)$ and $\mathcal{O}(p^4)$, which contain terms proportional to $m_u - m_d$, give values for the decay width $\Gamma(\eta \to \pi^+\pi^-\pi^0)$ that are significantly below the experimental value. A quadratic dependence arises at $\mathcal{O}(p^6)$. Parameterizing the decay amplitude as $|A|^2 \sim 1 + 2\alpha z$, where z is a measure of the distance from the center of the $3\pi^0$ Dalitz plot, we find $\alpha = -0.031 \pm 0.004$. This value is about 2–5 times theoretical estimates [15] and provides a challenge to all the theoretical descriptions.

5 Summary and outlook

The Crystal Ball program is providing a wealth of high-quality data on a variety of topics in baryon spectroscopy and meson decays. We find strong evidence for flavor symmetry in the threshold behavior of $\pi^- p \to \eta n$ and $K^- p \to \eta\Lambda$ reactions, as well as in $2\pi^0$ production reactions. Production of a σ meson is very small. Data for the decays of the η meson are providing strong constraints on the understanding of basic symmetries, and tests of χPT expansions.

The CB Collaboration is preparing for several new experiments at BNL. These include: (1) extended studies of hyperon resonances through $K^- p$ reactions; (2) precision measurements of the $\pi^- p \to \pi^0 n$ reaction at low energies, to explore issues in isospin symmetry and possibly to get new constraints on the $m_u - m_d$ quark mass difference; and (3) a precision determination of the $K^+ \to \pi^0 e^+ \nu$ (K_{e3}) decay rate to obtain an improved value of the CKM matrix element V_{us}, for a test of CKM unitarity.

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