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HIGHLIGHTS FROM THE CRYSTAL BALL PROGRAM AT THE AGS

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Results are presented for π^-- and K^--induced reactions on a proton target leading to all-neutral final states. Also shown are new data on rare and forbidden eta-meson decays. The detector is the Crystal Ball multi-photon spectrometer, which until recently was located in the C-6 secondary beam line at the AGS. Special emphasis is given to $2\pi^0$ production.

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1. Introduction

The Crystal Ball (CB) detector is a multiphoton spectrometer. It was constructed at SLAC and used there for the study of charm quarks. It also spent some time on B-physics at DESY. In 1995 the UCLA group brought it to BNL for a set of experiments on baryon physics with π^- and K^- incident on a liquid hydrogen target that was located at the center of the CB. The maximum beam momentum was 750 MeV/c. An extensive set of η decay spectra and upper limits on forbidden η decays were obtained using auto-tagged etas obtained in the reaction $\pi^- p \to \eta n$ near threshold.

The experiments carried out at BNL are listed in Table 1. Most of the data have been analyzed in some form. About half of these reactions have already been published in refereed journals. Many of the important results have been presented at conferences and meetings.

The bulk of the data were obtained in the fall of 1998. They are referred to as AGS experiments E913, E914 and E897. Some data were obtained with a solid CH_2 target in the spring of 2002 and are referred to E958.

The Crystal Ball consists of 672 optically isolated NaI(Tl) crystals, shaped like

TABLE 1. The reactions investigated by the Crystal Ball Collaboration at the AGS.

E913/958	E914	E897	
$\pi^- p \to \gamma n$	$K^- p \to \overline{K}^0 n$	$\eta \to 2\pi^0$	CP
$\pi^- p \to \pi^0 n$	$K^- p \to \pi^0 \Lambda$	$\eta \to 3\pi^0$	χPTh
$\pi^- p \to \pi^0\pi^0 n$	$K^- p \to \pi^0\pi^0 \Lambda$	$\eta \to 4\pi^0$	CP
$\pi^- p \to \pi^0\pi^0\pi^0 n$	$K^- p \to \pi^0\pi^0\pi^0 \Lambda$	$\eta \to \pi^0\gamma\gamma$	χPTh
$\pi^- p \to \eta n$	$K^- p \to \eta \Lambda$	$\eta \to 2\pi^0\gamma\gamma$	χPTh
$\pi^- p \to \gamma\pi^0 n$	$K^- p \to \gamma \Lambda$	$\eta \to 2\pi^0\gamma$	C
$\pi^- p \to \gamma\eta n$	$K^- p \to \pi^0 \Sigma^0$	$\eta \to 3\pi^0\gamma$	C
	$K^- p \to \pi^0\pi^0 \Sigma^0$	$\eta \to 3\gamma$	C
$\pi^- A \to 2\pi^0 X$	$K^- p \to \gamma \Sigma^0$	$\eta \to \pi^0\gamma$	J
$\pi^- A \to \pi^0 X$			
$\pi^- A \to \eta X$			

truncated triangular pyramids and arranged in two hemispheres that cover 93% of 4π steradians. The typical energy resolution for electromagnetic showers in the CB is $\Delta E/E = 0.020/[E(\mathrm{GeV})]^{0.36}$. Shower directions are measured with a resolution in θ, the polar angle with respect to the beam axis, of $\sigma_\theta = 2^\circ - 3^\circ$ for photon energies in the range $50-500$ MeV, assuming that the photons are produced in the center of the CB. The resolution in ϕ is $2^\circ/\sin\theta$. The experiments were performed with momentum-analyzed beams of negative pions and kaons, incident on a 10-cm-long liquid hydrogen target located at the center of the CB. The beam momentum spread σ_p/p at the CB target was about 1%. The mean momentum of the beam spectrum at the target center was known with an accuracy of $2-3$ MeV/c. The beam trigger was taken from the coincidence of three scintillation counters located in the beam line upstream of the CB. The CB event trigger had the beam trigger in coincidence with a Crystal Ball signal which included the requirement that the total energy deposited in the crystals exceeded a certain threshold. The neutral event trigger required the anti-coincidence of the CB event trigger with signals from a barrel of scintillation counters surrounding the target. More details about the CB detector and the data analyses can be found in Refs. [1] and [3].

2. *Multi-π^0 production by π^- and* K$^-$

The solid angle coverage of the CB is 93% of 4π steradians. The CB is especially well-suited to measure multi-π^0 production for which there is a dearth of data. Below we will highlight the results obtained on $2\pi^0$ and $3\pi^0$ production by π^- and K$^-$. The simplest $2\pi^0$ production reaction, $\pi^- p \to \pi^0\pi^0 n \to 4\gamma n$, is seen as a four or five cluster event, depending on whether the neutron is detected or not. Since we measure all particles except the neutron, we can use the constrained fit, or kinematic fit, to match the 4 photon clusters to give two unique π^0's. As a result, our data sample is clean, we estimate over 98%, and ample! The latter is important as the 3 particle final state needs a total of 5 kinematic variables for a complete description. If we divide each variable in just four parts, than at *each energy* we have $(4)^4 = 256$ different kinematic regions. We have collected over half a million $\pi^-\mathrm{p} \to \pi^0\pi^0\mathrm{n}$ events for 19 incident π^- momenta from threshold to $p_\pi = 0.75$ GeV/c, which dwarfs the published $2\pi^0$ data. Because the older data had small statistics and a limited angular coveage, it was often reported as a Dalitz plot of the invariant mass squared of the $\pi^0\pi^0$ system $\tilde{m}^2(\pi^0\pi^0)$ versus $\tilde{m}^2(\pi^0\mathrm{n})$ *integrated over all other kinematic variables.* Shown in Figs. 1a−d are our data at $p_\pi = 0.66$ GeV divided into four Dalitz plots (DP) for four regions of $\cos\theta_{\pi\pi}$ where $\theta_{\pi\pi}$ is the dipion angle in the c.m., along with the DP projections onto the x- and y-axes. It is ventured that the σ-meson could play a major role in $2\pi^0$ production. Specifically, we could have $\pi^-\mathrm{p} \to \mathrm{N}(1440)\frac{1}{2}^+ \to \sigma + \mathrm{n}$ followed by $\sigma \to 2\pi^0$. If the σ is a meson and not just a $\pi - \pi$ interaction, its mass and width should be the same at all $\theta_{\pi\pi}$ values. Clearly, that is not seen in Figs. 1e−h; also, $2\pi^0$ production via the σ is a pure s-wave process which manifests itself as a horizontal band in the DP's of Figs. 1a−d, reflecting the mass and width of the σ. This is not observed either.

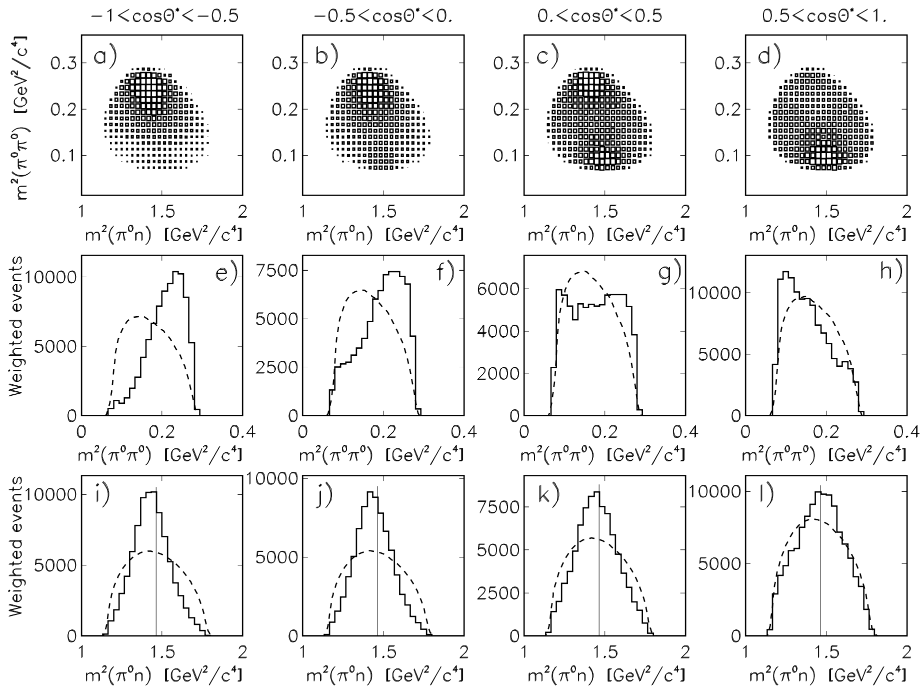

Fig. 1. The CB data for $\pi^-\mathrm{p} \to \pi^0\pi^0\mathrm{n}$ at $p_\pi = 0.66$ GeV/c. The top row contains Dalitz plots of the data, divided into four sets:sets: (a) $-1.0 < \cos\theta_{\pi\pi} < -0.5$; (b) $-0.5 < \cos\theta_{\pi\pi} < 0.0$; (c) $0.0 < \cos\theta_{\pi\pi} < 0.5$; (d) $0.5 < \cos\theta_{\pi\pi} < 1.0$. The second row (e–h) contains the projections of the Dalitz plots onto the $m^2(\pi^0\pi^0)$ axis. The third row (i–l) contains the Dalitz plot projections onto the $m^2(\pi^0 n)$ axis.

Another likely chain of reactions for $2\pi^0$ production is $\pi^-\mathrm{p} \to \mathrm{N}(1440)\frac{1}{2}^+ \to \pi_1^0 + \Delta^0$ followed by $\Delta^0 \to \pi_2^0 + \mathrm{n}$. This process should manifest itself as a vertical band in the DP.

Since both the decay of the N(1440) and the Δ are p-wave processes, we expect the Δ-band not to be homogeneous but to be depleted in the middle. Since the two π^0's are identical particles, we don't know which one is π_1^0 and which π_2^0. This problem is solved by employing a simple technique, namely plotting each event twice, once as $\tilde{m}^2(\pi_1^0\mathrm{n})$ and once as $\tilde{m}^2(\pi_2^0\mathrm{n})$. This causes the original vertical Δ -band in the DP to become slightly slanted and to widen a bit. The projection of the DP on the $\tilde{m}^2(\pi\mathrm{n})$ axis will be slightly skewed and be very similar for the four regions in $\theta_{\pi\pi}$; this is borne out by the data shown in Figs. 1i−l. We conclude that $2\pi^0$ production by π^- on a proton in the energy range of the CB experiment is dominated by the formation of the Δ and that a noteworthy contribution of the σ resonance to $2\pi^0$ production is not evident in the data.

We have over 20 000 events at most beam momenta and we cover the entire kinematical regime of the $\pi^0\pi^0$n final state, thus we have the necessary input data to calculate accurately the total cross section at every incident beam momentum.

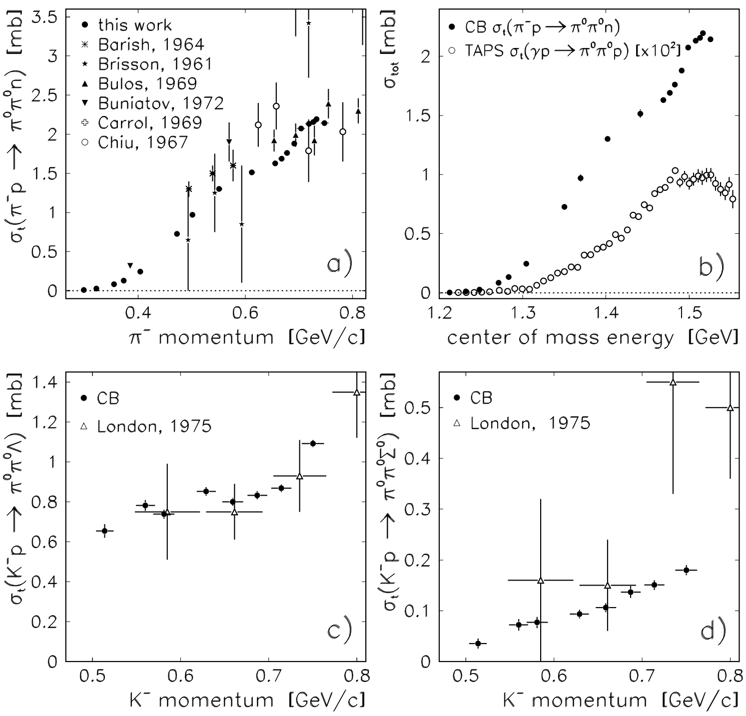

Fig. 2. (a) CB Results for $\sigma_{\mathrm{tot}}(\pi^-\mathrm{p} \to \pi^0\pi^0\mathrm{n})$ vs. p_π compared to existing data. (b) Comparison of $\sigma_{\mathrm{tot}}(\pi^-\mathrm{p} \to \pi^0\pi^0\mathrm{n})$ obtained by the CB with $\sigma_{\mathrm{tot}}(\gamma\mathrm{p} \to \pi^0\pi^0\mathrm{p})$ by TAPS. (c) Total cross sections vs. p_{K} for $\mathrm{K}^-\mathrm{p} \to \pi^0\pi^0\Lambda$ (d) Total cross sections vs. p_{K} for $\mathrm{K}^-\mathrm{p} \to \pi^0\pi^0\Sigma^0$.

Shown in Fig. 2a is $\sigma_{\rm tot}(\pi^-{\rm p} \to \pi^0\pi^0{\rm n})$ as a function of the incident π-beam momentum. Noteworthy in this figure is the shoulder in $\sigma_{\rm tot}$ near the pole value of the Roper N* resonance. It provides us with the first direct evidence in a total cross section for the reality of the elusive Roper which is such a broad state that it successfully hides under the tails of other resonances. Fig. 2a also shows a peak at the high end of our beam momentum. This peak is due mainly to the $2\pi^0$ decay of the $\rm N(1520)\frac{3}{2}^-$ with some contribution of the $\rm N(1535)\frac{1}{2}^-$.

It is of interest to compare $2\pi^0$ production by π^- with $2\pi^0$ photoproduction; the radiative coupling of the Roper is known to be small. The comparison is made in Fig. 2b which includes $\sigma_{\rm tot}(\gamma{\rm p} \to \pi^0\pi^0{\rm p})$ as measured at MAMI with the TAPS detector [4]. We have normalized the photoproduction cross sections by a factor of 100 which is a reasonable ballpark number for this.

Next we discuss new CB data on $\rm K^-p \to \pi^0\pi^0\Lambda$. The Λ decays to π^0n and each π^0 into a pair of photons. Thus $\pi^0\pi^0\Lambda$ final state shows up as a six or seven cluster event in the CB. The reaction under consideration is cleanly extracted using a 5C or 3C kinematic fit depending on whether or not the neutron is detected. The decay length of the Λ is a free parameter of the fit. Thus we can determine the half-life of the Λ. We have demonstrated this in the analysis of the $\rm K^-p \to \eta\Lambda$ reaction; see Ref. [3] where we have found good agreement with the known Λ decay lengths.

Shown in Fig. 2c is the excitation function for $\sigma_{\rm tot}(\rm K^-p \to \pi^0\pi^0\Lambda)$. Around $p_{\rm K} = 0.60$ GeV, much of the cross section is expected to come from the $\Lambda(1600)\frac{1}{2}^+$ hyperon which is the Λ analog of the Roper. There is also the onset of a peak at the highest available beam momentum which reflects the production of the $\Lambda(1670)\frac{1}{2}^-$ and $\Lambda(1690)\frac{3}{2}^-$.

The Lagrangian of QCD can be divided conveniently in two distinct parts: $\mathcal{L}_{\rm QCD} = \mathcal{L}_0 + \mathcal{L}_m$. The $\mathcal{L}_0$ part depends only on the quark and gluon fields; it is the same for all six quark flavors and goes under the name of the “flavor symmetry of massless QCD” (Flavor Symmetry). The Flavor Symmetry is broken by the quark mass term

$$\mathcal{L}_m = \sum_q \overline{\psi}_q m_q \psi_q .$$

As a consequence of Flavor Symmetry, one expects that there exists a Λ^* hyperon for every N* nucleon resonance with the same spin and parity, but heavier roughly by the s-d quark mass difference of about 140 MeV/c^2. We also observe that $\Gamma_{\Lambda^*} \simeq \Gamma_{\Sigma^*} \simeq \frac{4}{9}\Gamma_{\rm N^*} \simeq \frac{4}{9}\Gamma_{\Delta^*}$ [5]. The hyperon resonances are narrower than the N*, experimentally by about a factor of two. Threshold η production in the reaction $\rm K^-p \to \eta\Lambda$ measured also by the CB [3,6] is strikingly similar to $\pi^-{\rm p} \to \eta{\rm n}$. This shows that Flavor Symmetry is not limited to static properties but can be used in dynamics as well [3]. An important test case involving 3-body final-state reactions is to compare $2\pi^0$ production by $\rm K^-$ and π^-. It turns out that $\pi^-{\rm p} \to \pi^0\pi^0{\rm n}$ is the flavor analog of $\rm K^-p \to \pi^0\pi^0\Lambda$. All initial- and all final-state particles belong to the same octets. The intermediate states are the $\Delta(1232)\frac{3}{2}^+$ and $\Sigma(1385)\frac{3}{2}^+$

which belong to the same SU(3) decuplet. Thus we predict similar features in the two reactions. This is confirmed by our data; for instance, compare the Dalitz plots shown in Figs. 1a–d and 3a–d.

An entirely different scenario applies to $K^-p \to \pi^0\pi^0\Sigma^0$. Though incident and outgoing particles belong to the same octets, the intermediate Λ^* state cannot be an SU(3) decuplet state, because decuplet Λ's do not exist. The intermediate states are the $\Lambda(1405)\frac{1}{2}^-$ and the $\Lambda(1520)\frac{3}{2}^-$ both of which are SU(3) singlet states. Thus we predict that the DPs for $\pi^0\pi^0\Sigma^0$ and $\pi^0\pi^0\Lambda$ are quite different. This is shown in Figs. 3a–d and 3e–h, which also show that $\sigma_{\rm tot}(K^-p \to \pi^0\pi^0\Lambda) \neq \sigma_{\rm tot}(K^-p \to \pi^0\pi^0\Sigma^0)$ (see Figs. 2c–d). We have collected a useful sample of Λ(1405) decays to study the decay $\Lambda(1405) \to \pi^0\Sigma^0$. It might shed light on answering the popular question on the nature of the Λ(1405): is it a 3-quark object or a bound state of a baryon and meson?

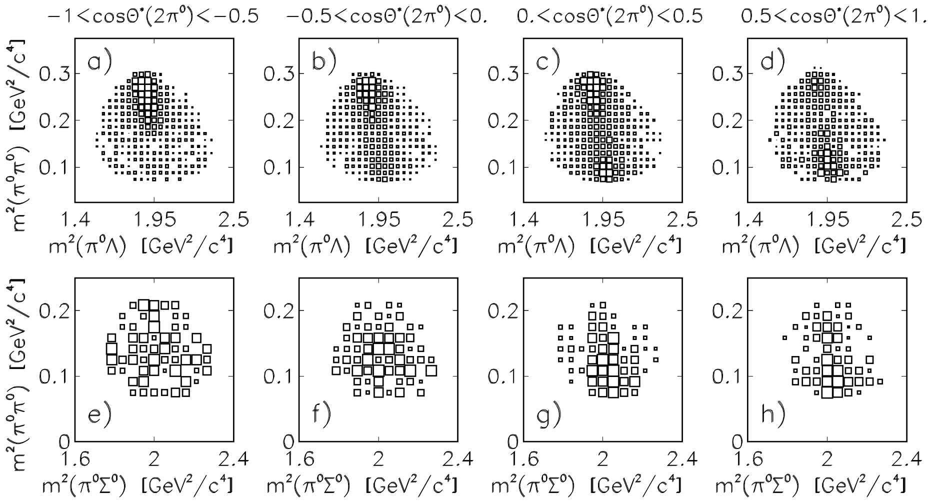

Fig. 3. (a–d) Same as Fig. 1a–d for $K^-p \to \pi^0\pi^0\Lambda$ *at* $p_K = 714$ MeV/c. *(e–h) Same as Fig. 1a–d for* $K^-p \to \pi^0\pi^0\Sigma^0$ *at* $p_K = 689$ MeV/c.

Measurements of $3\pi^0$ productions by π^- and K^- are of interest because they provide a way to obtain the decay widths of the sequential decay modes. The existing data are meager and of poor quality, and appear to be contaminated by $\eta \to 3\pi^0$ decays. The CB was used to measure $\sigma_{\rm tot}(\pi^-p \to \pi^0\pi^0\pi^0 n)$. The threshold for this process is at $p_\pi = 463$ MeV/c. The first signal is seen at $p_\pi = 653$ MeV/c, where the measured cross section is $\sigma_{\rm tot} = 2.5 \pm 0.5$ μb, and slowly rises to 23 ± 4 μb at 726 MeV/c. This value is 60 − 80 times smaller than the results obtained in previous experiments [7]. The natural explanation of our results is $3\pi^0$ production by sequential resonance decay involving three intermediate states

$$\pi^-p \to N(1535)\frac{1}{2}^- \to \pi^0 N^0(1440)\frac{1}{2}^+ \to \pi^0\left[\pi^0\Delta^0(1232)\frac{3}{2}^+\right] \to 3\pi^0 n\,.$$

Our data yield the following new branching ratio

$$BR\big[\mathrm{N}(1535) \to \pi\mathrm{N}(1440)\big] = 0.08 \pm 0.02\,,$$

not including theoretical uncertainties.

We have also investigated the related reaction $\mathrm{K}^-\mathrm{p} \to 3\pi^0\Lambda$. The total cross section is consistent with zero from threshold at $p_\mathrm{K} = 397$ MeV/c to $p_\mathrm{K} = 714$ MeV/c, with the upper limit at the 90% CL being $2 - 6$ μb. We see a signal where it is expected, namely at $p_\mathrm{K} = 750$ MeV/c with $\sigma_\mathrm{tot}(\mathrm{K}^-\mathrm{p} \to 3\pi^0\Lambda) = 25 \pm 7$ μb [8]. This should be compared with $\sigma_\mathrm{tot}(\mathrm{K}^-\mathrm{p} \to 2\pi^0\Lambda) = 0.8$ μb and $\sigma_\mathrm{tot}(\mathrm{K}^-\mathrm{p} \to \pi^0\Lambda) = 2.8$ μb. Both the $3\pi^0$ production experiments are of interest for learning about the phenomenology of conversion of kinetic energy into hadronic matter. Our results are consistent with the hypothesis that pion production is governed by the decay of specific excited nucleonic states and that spontaneous emission is not significant.

3. Hyperon physics

The Crystal Ball is well-suited for the detection and identification of hyperons and K^0_S-mesons; their decay modes, the branching ratios and decay lengths are given in Table 2. The CB also detects neutrons and K^0_L-mesons with a probability up to 40% depending on the energy. Only θ and ϕ information is obtained for a neutron or K^0_L; there is no reliable energy determination and no unique particle identification.

TABLE 2. The neutral decay modes, branching ratios, BR, and decay length, $c\tau$, of the hyperons and K^0_s -mesons detected with the Crystal Ball.

particle	decay mode	*BR* (%)	$c\tau$ (cm)
Λ	$\pi^0\mathrm{n} \to 2\gamma\mathrm{n}$	36	7.9
Σ^0	$\gamma\Lambda \to 3\gamma\mathrm{n}$	36	7.9
Σ^+	$\pi^0\mathrm{p} \to 2\gamma\mathrm{p}$	51	2.4
K_s	$2\pi^0 \to 4\gamma$	31	2.7

We have taken data simultaneously on all neutral K^--induced reactions; they are important for the determination of the properties of Λ and Σ hyperons. Shown in Fig. 4 are the energy dependences of the total cross sections

$$\begin{aligned}
\sigma\big(\mathrm{K}^-\mathrm{p} \to \overline{\mathrm{K}}^0\mathrm{n}\big) &= \frac{1}{4}\big|A_1 - A_0\big|^2, \\
\sigma\big(\mathrm{K}^-\mathrm{p} \to \pi^0\Lambda\big) &= \frac{1}{2}\big|A_1\big|^2 \times C_1, \qquad \text{and} \\
\sigma\big(\mathrm{K}^-\mathrm{p} \to \pi^0\Sigma^0\big) &= \frac{1}{6}\big|A_0\big|^2 \times C_2\,,
\end{aligned}$$

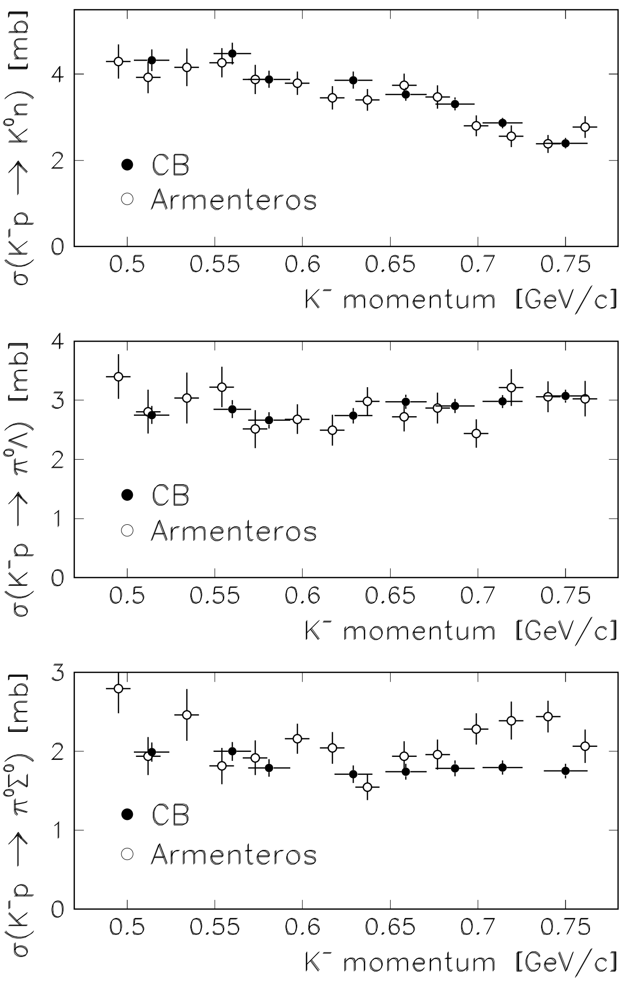

Fig. 4. Total cross section vs. p_K: (a) $K^-p \to K_s n$, *(b)* $K^-p \to \pi^0\Lambda$ *and (c)* $K^-p \to \pi^0\Sigma^0$.

where A_0 and A_1 are the isospin 0 and 1 amplitudes. C_1 and C_2 are the energy dependent phase space factors relative to $K^-p \to \overline{K}^0 n$, with C_1 typically 1.8 and C_2 about 0.9.

The intermediate states of the reaction $K^-p \to \pi^0\Lambda$ are pure Σ^*; the relevant ones are listed in Table 3. $K^-p \to \pi^0\Sigma^0$ only has Λ^* states while $K^-p \to \overline{K}^0 n$ features both in equal proportions. In the energy region covered by our experiment, $1.57 < \sqrt{s} < 1.68$ GeV, all three total cross sections vary little and they are of the same order of magnitude, as expected.

The differential cross sections have quite different shapes. The $\pi^0\Lambda$ final-state reaction is strongly peaked in the forward direction, the $\pi^0\Sigma$ reaction peaks in the backward direction and $\overline{K}n$ in both (see Fig. 5)! It is interesting that $d\sigma(\overline{K}^0 n)$ has the features of the combination of $d\sigma(\pi^0\Lambda)$ and $d\sigma(\pi^0\Sigma^0)$ at $p_K = 629$ MeV/c.

TABLE 3. Comparison of the N, Λ and Σ light resonances covered in the present CB run. All are SU(3) octet states except the Λ(1405) and Λ(1520), which are SU(3) singlets.

	Γ (MeV)		Γ (MeV)		Γ (MeV)
$N(938)\frac{1}{2}^+$	–	$\Lambda(1116)\frac{1}{2}^+$	–	$\Sigma(1192)\frac{1}{2}^+$	–
$N(1440)\frac{1}{2}^+$	∼ 350	$\Lambda(1600)\frac{1}{2}^+$	∼ 150	$\Sigma(1660)\frac{1}{2}^+$	100
$N(1520)\frac{3}{2}^-$	∼ 120	$\Lambda(1690)\frac{3}{2}^-$	60	$\Sigma(1670)\frac{3}{2}^-$	60
$N(1535)\frac{1}{2}^-$	∼ 150	$\Lambda(1670)\frac{1}{2}^-$	35	$\Sigma(1620)\frac{1}{2}^-$	–
		$\Lambda(1405)\frac{1}{2}^-$	50		
		$\Lambda(1520)\frac{3}{2}^-$	16		

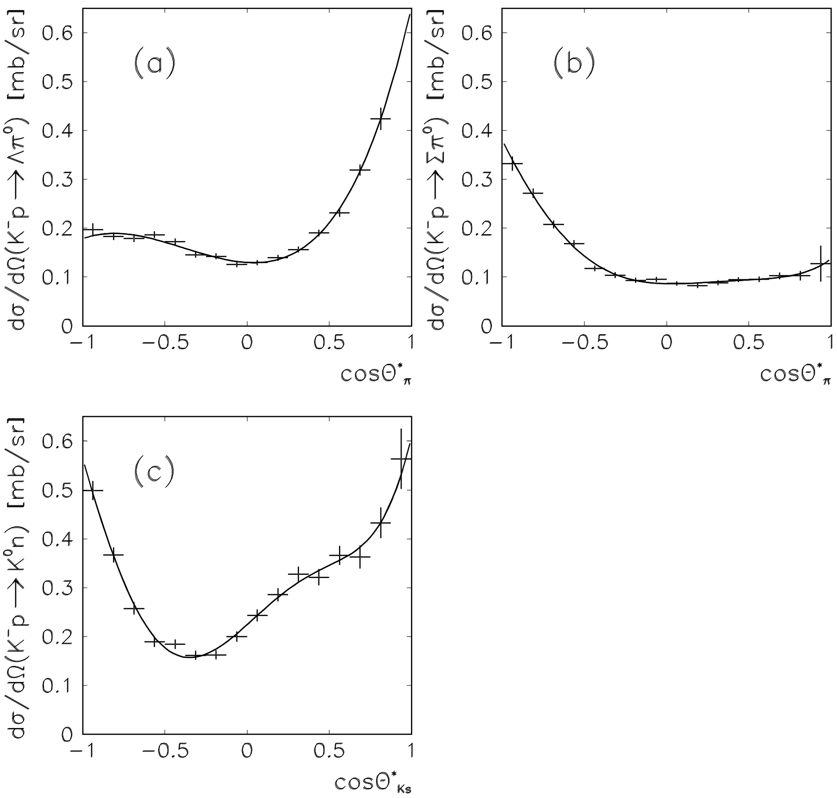

Fig. 5. Differential cross section at p_K = 629 MeV/*c*: *(a)* $K^-p \to \pi^0\Lambda$, *(b)* $K^-p \to \pi^0\Sigma^0$ *and (c)* $K^-p \to K_s\eta$.

4. Eta-meson decays

Broken symmetries such as chiral symmetry (χS), flavor symmetry (FS), and CP play a crucial role in particle and nuclear physics. Massless quarks have χS which is broken spontaneously giving rise to eight Goldstone bosons with $J^P = 0^-$ $(\pi^+, \pi^-, \pi^0, \mathrm{K}^+, \mathrm{K}^-, \mathrm{K}^0, \overline{\mathrm{K}}^0, \eta)$. These bosons interact strongly with one another, and the dynamics are governed by mesonic resonances, e.g. the ρ-meson is due to the strong P-wave $\pi - \pi$ interaction. This interesting perspective on the resonances implies that hadron dynamics at low energy is ultimately a consequence of the breaking of χS. Many calculations in this field (at low energy always) are performed using chiral perturbation theory (χPTh). It is important to provide the experimental foundation for the usefulness of χPTh, especially to show that the expansion used in χPTh converges sufficiently rapidly. The eta-meson provides a unique test of the third term in the expansion of χPTh, namely the branching ratio for $\eta \to \pi^0\gamma\gamma$. This decay is strictly forbidden in first order while the second order is strongly suppressed. Thus the decay rate for $\eta \to \pi^0\gamma\gamma$ is a direct test of third order χPTh, which is a unique case. Several calculations of the decay rate agree that the χPTh value is $\Gamma(\eta \to \pi^0\gamma\gamma) \simeq 0.4$ eV. The corresponding branching ratio $BR(\eta \to \pi^0\gamma\gamma)$ measured by the GAMS 2000 collaboration based on 38 events, is $(7.7 \pm 1.7) \times 10^{-4}$, or twice the χPTh favored value. The Crystal Ball at the AGS has obtained 500 events which yields $\mathrm{BR}(\eta \to \pi^0\gamma\gamma) = (3.2 \pm 0.9) \times 10^{-4}$ [10]. It is hoped that the CB at MAMI can verify this and measure the important Dalitz plot of this decay.

Another interesting decay is $\eta \to 3\pi^0$. The $3\pi^0$ decay violates isospin invariance, so the decay occurs as a consequence of the up-down quark mass difference which induces $\pi^0 - \eta$ mixing. This follows directly from QCD. The $\mathcal{L}_0$ part of the QCD Lagrangian does not contribute due to isospin invariance leaving only $\mathcal{L}_m = \sum_q \overline{q} m_q q$. Applying this to $\pi^0 - \eta$ mixing, we have

$$\begin{aligned}\langle \pi^0 | H_m | \eta \rangle &= \langle \frac{1}{2}\sqrt{2}(\overline{u}u - \overline{d}d) | \overline{u} m_{\mathrm{u}} u + \overline{d} m_{\mathrm{d}} d | \frac{1}{3}\sqrt{3}(\overline{u}u + \overline{d}d - \overline{s}s) \rangle \\ &= \frac{1}{6}\sqrt{6}\big(m_{\mathrm{u}} - m_{\mathrm{d}}\big) \,. \qquad (1)\end{aligned}$$

Since $\Gamma(\eta \to 3\pi) \sim (m_{\mathrm{u}} - m_{\mathrm{d}})^2$, it turns out that one of the best ways to determine the up-down quark mass difference is from $\Gamma(\eta \to 3\pi)$; also the ratio $R \equiv \Gamma(\eta \to 3\pi^0)/\Gamma(\eta \to \pi^+\pi^-\pi^0)$ depends on the s-d mass difference.

An interesting parameter is the density variation, or the "slope", of the $\eta \to 3\pi^0$ Dalitz plot. In lowest order, the slope is zero because the final state consists of three identical π^0's. However, the $\pi - \pi$ interaction is energy dependent resulting in a small variation in the DP: $|M|^2 = 1 + 2\alpha z$, where M is the matrix element and z is a variable indicating how far the decay is from the center of the DP. The best result until recently was $\alpha = 0.052 \pm 0.007 \pm 0.010$ from the Crystal Barrel at LEAR. The CB, using a 40 times larger sample, has obtained $\alpha = -0.031 \pm 0.004$ [2]. Theoretically the best available calculation gives α in the range -0.014 to -0.007.

5. *Searches for new physics in forbidden eta-meson decays*

The Standard Model (SM) of electroweak interactions has been very successful at making quantitative predictions for many electroweak processes. The SM is not considered to be a complete physics theory for several reasons. It needs no less than 17 input parameters, not including the neutrino sector. It does not explain the existence of three families, the left-handedness of the neutrinos, the vastly different masses of the 6 quarks and 3 charged leptons, and the origin of CP violation. A good area to look for new physics beyond the SM is the limit of validity of the C, P, T, CP, and CPT symmetries.

There is a special interest in C-invariance or charge-conjugation symmetry. This concerns the comparison of the properties and interactions of matter and antimatter, a well-known cosmological problem in the abundance of matter over antimatter in the universe. The big bang models of cosmology imply the same abundance of matter and antimatter. Experiments to test C and CP invariance are rare because they require a system of particles which is symmetric under the interchange of matter and antimatter. This limits our choice to electrically neutral and flavorless systems which are hard to find. Fortunately, the eta is an eigenstate of the CP and C-operators.

Shown in Table 4 are one novel test of CP, two novel tests of C invariance, and one familiar test of C done with the CB at the AGS. We have included the sensitivity of each test, which is defined as the ratio of the amplitude for the forbidden decay divided by the amplitude for a comparable allowed process. Details are given in Ref. [10].

TABLE 4. Tests of C and CP invariance using forbidden eta decays that were done at the AGS using the CB.

decay	test	upper limit	sensitivity
$\eta \to 4\pi^0$	CP	$< 6.9 \times 10^{-7}$	2.3×10^{-2}
$\eta \to \pi^0\pi^0\gamma$	C	$< 5 \times 10^{-4}$	1.7×10^{-2}
$\eta \to \pi^0\pi^0\pi^0\gamma$	C	$< 7 \times 10^{-5}$	3.6×10^{-3}
$\eta \to 3\gamma$	C	$< 1.8 \times 10^{-5}$	

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NAJVAŽNIJI ISHODI PROGRAMA S KRISTALNOM LOPTOM U AGS-U

Opisujemo ishode mjerenja reakcija izazvanih π^-- i K^--mezonima na protonima koje vode na stanja samih neutralnih čestica. Prikazujemo također nove podatke o rijetkim i zabranjenim raspadima eta mezona. Primjenjuje se više-fotonski spektrometar Crystal Ball koji je do nedavno bio na sekundarnom snopu C-6 u AGSu. Posebna se pažnja pridaje tvorbi $2\pi^0$.