Highlights of Crystal Ball Physics

B.M.K. Nefkens for the Crystal Ball Collaboration

UCLA, Los Angeles, CA 90095, USA

Differential and total cross sections are presented for $\pi^-$- and $K^-$-induced reactions on a proton target leading to all-neutral final states. Also shown are rates for rare and upper limits for forbidden eta-meson decays to test Chiral Perturbation Theory, the $\pi^0\pi^0$ interactions and $C$ and $CP$ invariance.

Keywords: Crystal Ball; Flavor Symmetry; Meson Scattering; $2\pi^0$ production; eta decays

1. Introduction

The Crystal Ball (CB) is a multiphoton spectrometer whose outstanding features include an acceptance that is 93% of $4\pi$ steradian; it uses a simple trigger which is based on the total energy deposited in the ball. The CB typically measures seven reactions simultaneously covering the full 180° angular range at once. These features have made the CB an exceptionally productive detector. The main detection elements are 672 isolated NaI(Tl) crystals arranged in two matching hemispheres with 336 windows each. There is an entrance and exit channel for the beam, and a cavity in the center for a liquid $H_2$ target. A veto-barrel counter surrounds the target. The CB has excellent energy and spatial resolutions. The CB can detect many photons at once, making it our detector of choice for measuring the production rates and spectra of final states which include $\gamma$, $\pi^0$, $2\pi^0$, $3\pi^0$, and $\eta$. We have demonstrated that the CB is also an excellent detector for neutrons as well as for $\Lambda \rightarrow \pi^0 n \rightarrow 2\gamma n$, $\Sigma^0 \rightarrow \gamma \Lambda \rightarrow \gamma \pi^0 n \rightarrow 3\gamma n$, $\Sigma^+ \rightarrow \pi^0 p \rightarrow 2\gamma p$, and $K^0 \rightarrow 2\pi^0 \rightarrow 4\gamma$.

We have performed four types of experiments using the AGS C6 beam line with separated $\pi^-$ and $K^-$ beams. The maximum beam momentum was 750 MeV/c. The CB is now at Mainz for an extensive program of linearly and circularly polarized photons interacting with a polarized proton or deuteron target producing the same particles that we measured at the AGS, with $E_\gamma$ up to 1.5 GeV. We also have a program on $\eta$, $\eta'$, and $\omega$ decays. The priority measurements are those of the magnetic dipole moment of the $\Delta^+(1232)$ and $N^+(1535)$ resonances. Other reports on AGS work with the CB include inverse photoproduction, shown by W. Briscoe; $\pi^- p$ charge exchange (CEX) in the region of the $\eta$ cusp, shown by S. Starostin; and low-energy CEX, shown by M. Sadler.

The CB is especially suited for intermediate energy physics, which includes:
2. Eta-Meson Production by $\pi^-$ and $K^-$

The production of the $\eta$ in the reactions $\pi^- p \rightarrow \eta n$ and $K^- p \rightarrow \eta \Lambda$ from threshold to 750 MeV/c has been measured in detail. When comparing the results for the two reactions one is struck by the similarities between them:

a) the identical, sharp onset of $\eta$ production directly at the opening of the $\eta$ channel;
b) the total cross section $\sigma_t$ has a strong peak not far above threshold for both reactions;
c) for threshold S-wave production, described by $\sigma_t = C \tilde{p}_\eta$, the constant $C$ is the same for both reactions within errors;
d) the angular distributions of the differential cross sections have a similar shape, which is like a shallow bowl, for both reactions;
e) the $\eta n$ and $\eta \Lambda$ scattering lengths are both large and attractive;
f) the intermediate states, the $N(1535)$ and the $\Lambda(1670)$ have the same spin and parity ($J^P = \frac{1}{2}^-$) and the same SU(3) classification;
g) the branching ratio into the $\eta$ channel of both intermediate states is anomalously large.

The above is readily explained by invoking dynamic flavor symmetry.
in $\eta$ production by $\pi^-$ and $K^-$. Consequently, in the limit of massless quarks, $\eta$ production by $\pi^-$ and $K^-$ should be identical. When the quarks have mass the QCD Lagrangian must be expanded by the quark-mass term, $\mathcal{L}_m$, where $\mathcal{L}_m = \overline{q}m_q q$. The effect of the mass term is to break the degeneracy. This causes the physical particles to have different masses, which leads to a different phase space for various processes, but it should not change much the overall dynamics of a reaction. There should be no radically different new features for two formerly degenerate SU(3)$_F$ symmetric reactions. The gross dynamic features such as a sharp onset of $\eta$ production, the $S$-wave dependence of $\sigma_t$, and the shape of the angular distribution should be similar for $\pi^- p \rightarrow \eta n$ and $K^- p \rightarrow \eta \Lambda$, as we have experimentally observed and discussed.

The consequences of the breaking of the SU(3)$_F$ symmetry due to the different masses of the quarks depends on the parameter and the process. SU(3)$_F$ implies that there is one $\Lambda^*$ resonance of the same spin and parity for every $N^*$ resonance, which is observed experimentally. The breaking due to the mass term causes the $\Lambda^*$'s to be some 140 MeV heavier than their $N^*$ partners, as is also observed. The $\mathcal{L}_m$ term lies at the heart of the success of the famous Gell-Mann-Okubo mass relations between the ground states of the octet and decuplet baryons.

The importance of SU(3)$_F$, even when it is broken, is the role it can play in the hunt for exotica, the non-three-quark baryons, the hybrids, the meson-baryon bound states and the non-unique pentaquarks. SU(3)$_F$ provides a novel way to search indirectly for the so-called missing $N^*$ and $\Lambda^*$ resonances. SU(3)$_F$ implies an important relation between the baryons: for every $N^*$ state there must be the three partners, a $\Lambda^*$, $\Sigma^*$, and $\Xi^*$ octet state with the same spin and parity and heavier by one or two $\Delta M_{sd}$ which is the mass difference between the $s$ and $d$ quarks. For every $\Delta^*$ there must be three decuplet partners, a $\Sigma^*$, $\Xi^*$, and $\Omega^*$ hyperon with the same $J^P$ and one, two, or three $\Delta M_{sd}$ heavier. There are also a few $\Lambda^*$ SU(3)$_F$ singlet states. A hyperon that does not fit this recipe is exotic, or a missing hyperon. Some examples:

- a) The $\Sigma(1580)^{-\frac{3}{2}}$ is only a one-star state. There is no missing or matching $N^*$ or $\Delta^*$ in the relevant mass region. Recent measurements by the CB of $K^- p \rightarrow \pi^0 \Lambda$ have not found evidence for this state. Very likely this $\Sigma(1580)$ does not exist and should be removed from the particle-properties compilation.

- b) The $\Xi(1620)$ is another one-star state awaiting confirmation (or removal); the mass is too low to be a $3q$ state.

- c) SU(3)$_F$ implies that the $\Xi(1690)$ has $J^P = \frac{1}{2}^+$. The second lightest excited state of the nucleon is the Roper with $J^P = \frac{1}{2}^+$ so the second lightest $\Xi^*$ should be the Roper analog and have $J^P = \frac{1}{2}^+$ also.

One of the reasons it has been so difficult to investigate the so-called missing $N^*$ and $\Delta^*$ resonances is the fact that these states are expected to be very broad with $\Gamma$ of 400–500 MeV. They overlap with each other and with neighboring states. It so happens that all known $\Xi^*$ resonances are narrow. A careful search for new
cascade states could confirm that certain “missing” $N^*$ or $\Delta^*$ are also missing $\Xi$ states. This would indicate that they actually are not missing states but do not exist.

A subgroup of SU(3)$_F$ is SU(2)$_F$. It is the basis of isospin, charge symmetry and G-parity invariance. Since the up-down quark mass difference is only a few MeV, there is abundant evidence for approximate isospin invariance in nuclear physics such as the near equality of the masses of isospin multiplet partners. There is also ample evidence for dynamic SU(2) flavor symmetry in the near equality of many isospin related reaction cross sections and angular distributions.

4. $\pi^0\pi^0$ Production by $\pi^-$ and $K^-$

The Crystal Ball is eminently suited for measuring $\pi^0\pi^0$ production by $\pi^-$, $K^-$, and $\gamma$. It will be interesting to see whether dynamic flavor symmetry is applicable to three-body final state reactions with their greater complexity. Consider the case of $K^-p \rightarrow \pi^0\pi^0\Lambda$ at $p_K = 750$ MeV/$c$. We can assume that the reaction is dominated by the $s$-channel processes. There are two quite different processes which are likely to be important:

a) $f_0(600)$ production from the two-body decay of the $\Lambda^*$ intermediate state, followed by the decay of the $f_0$ into $\pi^0\pi^0$, thus, $K^-p \rightarrow \Lambda^* \rightarrow f_0\Lambda \rightarrow \pi^0\pi^0\Lambda$. The dominant $\Lambda^*$ intermediate states are the $\Lambda(1670)\frac{1}{2}^-$ and/or the $\Lambda(1690)\frac{3}{2}^+$. This process is characterized by a broad, uniform band in the Dalitz Plot (DP) centered around the mass of the $f_0(600)$. In our choice of coordinates, which is $\tilde{m}^2(\pi^0\pi^0)$ for the vertical axis where $\tilde{m}(\pi^0\pi^0)$ is the invariant mass of the $\pi^0\pi^0$ system, while the horizontal axis shows $\tilde{m}^2(\pi^0\Lambda)$, the $f_0$ band should be horizontal.

b) The competing possibility is the sequential decay of two hyperons, specifically, $K^-p \rightarrow \Lambda^* \rightarrow \pi^0\Sigma(1385)\frac{3}{2}^+ \rightarrow \pi^0\pi^0\Lambda$. This mode is characterized by a strong vertical band with $\tilde{m}^2(\pi^0\Lambda)$ centered around the mass of the $\Sigma^0(1385)$.

There are two indistinguishable $\pi^0$'s in the final state. We don’t know which $\pi^0$ comes from $\Lambda^*$ and which from $\Sigma^0$ decay. We solve this dilemma by plotting both options on the DP. This has as a consequence that the vertical band will be slightly slanted. Furthermore, there are two $\pi^0\Lambda$ scattering amplitudes contributing to the final state which interfere with one another, causing the vertical band to be non-uniform. Destructive interference could even cause a void in the band. When option a) is dominant we expect that the related reaction $K^-p \rightarrow \pi^0\pi^0\Sigma^0$ will have a $\sigma_t$ similar to $K^-p \rightarrow \pi^0\pi^0\Lambda$, and that the two reactions will have similar DP’s. For option b) the intermediate state to the $\pi^0\pi^0\Sigma^0$ final state are $\Lambda^*$ resonances with different $J^P$, and we expect different $\sigma_t$’s and DP’s. Experimentally at 750 MeV/$c$ we find $\sigma_t(K^-p \rightarrow \pi^0\pi^0\Lambda = 6\sigma_t(K^-p \rightarrow \pi^0\pi^0\Sigma^0)$ and the DP’s are different, and there is no uniform horizontal band, thus the sequential decay of 2 hyperon
resonances plays the dominant role in $2\pi^0$ production.

Flavor symmetry relates $\pi^0\pi^0$ production by $K^-$ to that by $\pi^-$. Around 750 MeV/c beam momentum the dominant channels are:

A) $K^-p \rightarrow \Lambda^*{3\over 2}^- \rightarrow \pi^0\Sigma^0(1385){3\over 2}^+ \rightarrow \pi^0\pi^0\Lambda$

B) $K^-p \rightarrow \Sigma^*{3\over 2}^- \rightarrow \pi^0\Lambda(1405){1\over 2}^- \rightarrow \pi^0\pi^0\Sigma^0$

C) $\pi^-p \rightarrow N^*{3\over 2}^- \rightarrow \pi^0\Delta(1232){3\over 2}^+ \rightarrow \pi^0\pi^0n$

D) $\gamma p \rightarrow N^*{3\over 2}^- \rightarrow \pi^0\Delta(1232){3\over 2}^+ \rightarrow \pi^0\pi^0n$

Reaction D) is $\pi^0\pi^0$ photoproduction which is an electromagnetic interaction and QCD does not apply to the $\gamma p$ system. In reaction C) and D) the intermediate $N^*$'s actually are different mixtures of the $N^*{3\over 2}^+$ and the $N^*{1\over 2}^-$. We expect the DP for C) and D) not to be the same.

Every particle that appears in process A) is an SU(3)$_F$ analog state of every particle in the same role as process C). It follows then that the DP for $\pi^0\pi^0\Lambda$ should have the same features as $\pi^0\pi^0n$. This is what is observed.

On the other hand, the intermediate states in A) and B) are not flavor analog states. The $\Sigma(1385){3\over 2}^+$ belongs to a decuplet, as does the $\Delta(1232){3\over 2}^+$. The $\Lambda(1405){1\over 2}^-$ is a singlet state, thus we expect the DP for B) to be different than for A) which is also observed.

We have sufficient $\pi^0\pi^0$ data to enable us to study the dependence of the DP on its kinematic variables, specifically on $\theta_{\pi\pi}$ which is the angle of the $\pi^0\pi^0$ system in the center of mass and which is the complement of the recoil neutron angle $\theta_n$. The DP of the 750 MeV/c data depends strongly on $\theta_{\pi\pi}$. This is illustrated using the DP projection onto the $\pi^0\pi^0$ invariant mass coordinate in Fig. 1. For the process $\pi^-p \rightarrow \pi^0\pi^0n$ at forward $\theta_{\pi\pi}$ the DP is peaked at small $\hat{m}(\pi^0\pi^0)$, while for the backward $\theta_{\pi\pi}$ the DP peaks at the highest available $\hat{m}(\pi^0\pi^0)$. Dynamical SU(3) symmetry implies that the $\theta_{\pi\pi}$ dependence is the same for A and C. This is observed, as seen in Fig. 1. In some sense the similarity in the features of the four DP's for $\pi^0\pi^0\Lambda$ and $\pi^0\pi^0n$ in Fig. 1 is one of the most spectacular manifestations of flavor symmetry seen so far.

There is much more interesting physics in the $\pi^0\pi^0$ production data; space limitation prevents us from discussing it here. We only give two particularly striking examples.

1. The excitations function of $\sigma_1(\pi^-p \rightarrow \pi^0\pi^0n)$ has a clear shoulder at the pole position of the Roper (1440) resonance. It is a rare example of a direct manifestation of one of the most elusive states of the $N^*$ family.

2. Our data on $K^-p \rightarrow \pi^0\pi^0\Sigma^0$ at 750 MeV/c contains a good size sample of $\Lambda(1405) \rightarrow \pi^0\Sigma^0$ decays. The spectral shape of this decay is of interest to many theorists who have models for the $\Lambda(1405)$ being either a bound state or an overlapping set of two nearby states. The data is open to discussion!
5. Eta-Meson Decays

The decay mode \( \eta \to 3\pi^0 \) provides a special test of our understanding of the low-energy \( \pi^0\pi^0 \) interaction, which is the simplest known strong interaction and is free of the complication associated with the Coulomb interaction of charged particle processes. The \( \eta \to 3\pi^0 \) Dalitz plot has a three-fold symmetry because of the three indistinguishable \( \pi^0 \)'s, but it should not be entirely uniform because the \( \pi-\pi \) interaction is energy dependent. One can readily symmetrize the DP using as the variable the distance \( z \) to the center of the DP. \[^8\] The projection of the DP density along the \( z \)-axis is then given by \( |A| = 1 + \alpha z \), where \( \alpha \) is the slope parameter. Four previous experiments have been inconclusive. Using a sample of 19 M \( \eta \)'s, the slope parameter was found to have the same sign (negative) as the theoretical calculation by Kambor et al. \[^9\], but numerically two and a half times as big. \[^8\]

The decay width of the rare decay \( \eta \to \pi^0\gamma\gamma \) provides a gold-plated test of chiral perturbation theory, \( \chi PT h \), because it is a direct test of the 3rd-order term. This unique feature comes about because the first order term is zero since the neutral \( \pi^0 \) and \( \eta \) meson do not couple in lowest order to the photon. The second order is ignorably small because the relevant decay channels violate G-parity. Various theoretical evaluations of the decay rate with \( \chi PT h \) or by other means such as vector-meson dominance agree that \( \Gamma(\eta \to \pi^0\gamma\gamma) \simeq 0.4eV \). After 13 unconvincing attempts, there is only one modern measurement. It was made by GAMS-2000, who
reported a $\Gamma$ of about 0.8 eV, double the theoretical value. The CB, using a sample of 28 $\eta$'s, found 1600 events leading to $\Gamma(\eta \rightarrow \pi^0\gamma\gamma) = 0.45 \pm 0.12$ eV, a result that thrills the theorists.\[10,11\]

There is considerable interest in improved tests of $C$-invariance of the strong interactions. Firstly, because of the observation of the excess of matter over antimatter in the universe, it does not agree with the big bang model. Secondly, because of the structural asymmetry of the Standard Model that groups the basic quark and lepton constituents in left-handed doublets but right-handed singlets.

The $\eta$ meson makes possible several novel tests of $C$-invariance by searching for $C$-forbidden decays into $\pi^0\pi^0\gamma$ and $\pi^0\pi^0\pi^0\gamma$. The sensitivity of these tests is readily evaluated by comparison with $C$-allowed decays.\[11\] The CB has determined the first upper limit, $BR(\eta \rightarrow \pi^0\pi^0\gamma) < 5 \times 10^{-4}$. This implies that $A_\phi/A_c < 2.5 \times 10^{-3}$ where $A_\phi$ is the amplitude of a possible $C$-violating isoscalar interaction and $A_c$ is the allowed one. The CB also found $BR(\eta \rightarrow \pi^0\pi^0\pi^0\gamma) < 6 \times 10^{-5}$ which implies $A_\nu/A_c < 3.4 \times 10^{-3}$ where $A_\nu$ is the isovector $C$-violating amplitude.

6. Summary and Conclusion

A selection from the data obtained with the Crystal Ball multiphoton spectrometer at the AGS has been presented. The results are used to investigate various broken symmetries, in particular, flavor, isospin, charge, and chiral symmetry, and $C$-invariance. We have made a direct test of third-order $\chi PTh$ in $\eta \rightarrow \pi^0\gamma\gamma$ and of the $\pi^0\pi^0$ interaction via the slope parameter in $\eta \rightarrow 3\pi^0$ decay.

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