NEW RESULTS ON MESON PHYSICS WITH THE CRYSTAL BALL DETECTOR*

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New results (preliminary) are presented on studies of different broken symmetries such as chiral symmetry, SU(3) flavor, C and CP, obtained with the Crystal Ball multiphoton spectrometer. We have data on $\pi^- p$ and $K^- p$ interactions to various neutral final states up to a beam momentum of 760 MeV/c. We also present results on different neutral η-meson decays. Finally we show data on $2\pi^0$ production by 408 MeV/c π^- on complex nuclei to investigate nuclear medium modifications.

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1. Introduction

The research carried out with the Crystal Ball multiphoton detector can be characterized as studies of broken symmetries.

1. One of the most important broken symmetries in nuclear and particle physics is isospin which is the invariance of the strong interactions under the interchange of the up and down quarks. The quark mass cannot be measured directly because of the special QCD feature of "infrared

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slavery", only the quark mass difference is a measurable quantity. The sole way for determining $m_u - m_d$ is by measuring isospin or charge-symmetry breaking [1].

2. The natural extension of SU(2) is SU(3)-flavor symmetry which is achieved by including the strange quark. In QCD the strange quark is much like a down quark, it has the same basic strong interactions, except that it is somewhat heavier. Experimentally, $m_{\mathrm{s}} - m_d \simeq 150$ MeV. The only way to determine $m_s - m_d$, is through selected measurements of SU(3)-flavor breaking.

3. The discrete symmetries of P, C and T are broken by the weak interactions. According to QCD, regions of far away galaxies. An ugly feature of the Standard Model of electroweak interactions is the occurrence of evidence for C and T invariance is skimpy [2,3]. There are some important reasons for wanting better tests of C and T namely the well established particle–antiparticle asymmetry of the universe and the quark and lepton doublet–singlet asymmetry of the Standard Model. The universe is comprised predominantly of matter with little antimatter, there is no evidence for 67 MeV gammas from matter–antimatter annihilation coming from the border regions of far away galaxies. An ugly feature of the Standard Model of electroweak interactions is the occurrence of the elementary fermions in three families of left-handed doublet and right-handed singlet sets of quarks and leptons.

4. CP is a challenging symmetry. It is known to be broken on a small scale and so far has only been seen in the neutral K-meson system. The origin of CP violation appears to be an obscure phase in the C–K–M mass matrix. It is particularly difficult to study CP invariance experimentally in strong and electromagnetic interactions in which there is no flavor change.

5. In modern nuclear physics much attention is paid to studies of chiral symmetry, χS, which is broken by the quarks mass and by the vacuum. The latter gives rise to the quark condensate, $\langle \bar{q} \mid q \rangle \simeq -(230\ \mathrm{MeV})^3$, it accounts for some 98% of the proton's rest mass. The broken χS of ordinary matter is expected to be restored at high density and temperature. Currently one of the fashionable subjects is the onset of partial χS restoration at intermediate energy and density. This manifests itself in nuclear medium modification of the mass and width of mesons and baryons and in the occurrence of parity doublets in the spectrum of excited nucleons and hyperons.

The above broken symmetries, as well as others, may be investigated experimentally using the Crystal Ball for measuring the neutral final states which are produced in π^- and K^- interactions in hydrogen.

2. The Crystal Ball detector

The Crystal Ball, CB, is a multiphoton spectrometer with a nearly 4π geometrical acceptance. EM showers are measured with excellent energy and angular resolutions [4]. The CB is a sphere made of 672 separate NaI crystals. There is a small cavity in the center and there is an entrance and exit tunnel for the beam, see Fig. 1. The CB was originally built at SLAC, it has been moved to BNL where it is stationed at the AGS in a separated π^- and K^- beam with a maximum momentum of 760 MeV/c. A 10 cm liquid hydrogen target has been installed in the cavity in the center of the ball. The target is surrounded by a veto-barrel scintillator to insure that neutral final states are measured.

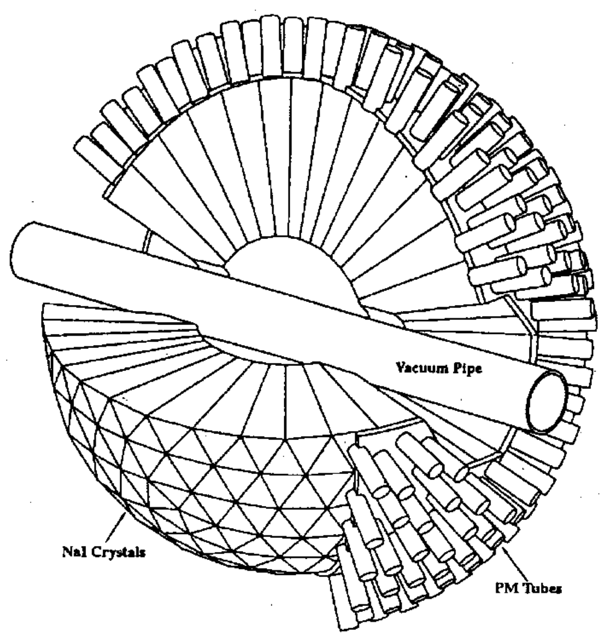

Fig. 1. Geometry of the Crystal Ball. Not shown are the 10 cm long liquid hydrogen target in the center and the 1.2 m long veto barrel which surround the target and vacuum pipe.

3. The eta meson

The η-meson has several useful features:

1. The η is an eigenstate of the P, C and CP operators. This allows for clean tests of P, C, CP invariance and even CPT.

2. The decay width of the η is 1.1 KeV, this should be compared to the typical strong width of 150 MeV. Thus, η decays are five orders of magnitude more sensitive than comparable ρ, a_0 and f_0-meson decays.

3. $\eta \to 3\pi$ is forbidden by isospin, charge symmetry or G-parity invariance. Thus it is a suitable candidate for determining $m_u - m_d$.

4. The η restmass is 547.3 MeV$/c^2$. This is sufficiently large to allow many useful decay modes to occur for the investigation of various broken symmetries.

5. The η is the most massive of the eight pseudoscalar bosons associated with spontaneously broken chiral symmetry, χS. The η is a good prospect for investigating χS breaking and for chiral perturbation theory.

6. The η belongs to the light pseudoscalar meson SU(3)-flavor nonet. This allows for $\pi^0 - \eta$ and for $\eta - \eta^{'}$ mixing which are important in evaluating SU(2)- and SU(3)-flavor breaking.

7. The ηN and $\eta \Lambda$ scattering lengths are large and the η-baryon interaction is attractive. This has given rise to speculations about the existence of exotic nuclear matter: eta-mesic nuclei and hypernuclei [5].

8. The η has isospin zero which allows it to play a special role in baryon spectroscopy. Consider $K^- p \to Y^* \to \eta \Lambda$. The initial state has $I = 0$ and 1. The η and Λ both are isoscalar particles, thus, the Y^* intermediate state must be a Λ^* hyperon resonance.

9. Some S-state baryons have a prominent η decay channel which is much larger that the π or K decay modes favored because of the larger phase space. The η can be used as a tracer of these S-state baryons.

10. The two largest η decay modes are $\eta \to 2\gamma$, BR $=$ 39.2% and $\eta \to 3\pi^0$, BR $=$ 32.2% this makes the Crystal Ball an especially practical detector for studying η production.

Note: The results shown in the next four chapters are **preliminary**.

4. $K^- p \to$ neutrals

4.1. $K^- p \to \eta \Lambda$

The $\sigma_t(K^- p \to \eta \Lambda)$ excitation function is shown in Fig. 2. The η is detected by the 2γ decay mode and the Λ by $\pi^0 n$. The Λ mean life is 0.26 nsec, the decay distance is 7.9 cm. The $\eta\Lambda$ final state gives rise to a two vertex final state. The intermediate state is the $\Lambda(1670)$ $S01$ resonance. Up to 20 MeV/c above threshold $\sigma_t \sim p_\eta^2$ this is characteristic of S-wave production. The branching ratio for $\Lambda(1670) \to \eta\Lambda$ is listed as $15-35\%$ [2]. The Λ polarization is easily measured with the CB, it is small, see Fig. 3, consistent with S-wave production. One of the consequences of SU(3)-flavor symmetry is replication. For instance the lambda octet states are the replicas of the N^* resonances, they have the same isospin/parity but are heavier by about 135 MeV. The $\Lambda(1670)$ $S01$ is the replica state of the $N(1535)$ $S11$ and has similar properties. The $N(1535)$ $S11$ has a large η decay, BR $\simeq$ 51%. To account for this large branching ratio, which for reasons of phase space should be much less than for πN, it has been suggested that the $N(1535)$ is not an ordinary three-quark state but a quasi-bound ΛK and ΣK state [6]. Such quasi-bound states are not SU(3)-flavor symmetric, there is then no obvious reason to expect that the $\Lambda(1670)$ decays also by η emission with BR = 20–35%. Close to threshold η production is mainly S-wave leading to a flat angular distribution. Due to a small contribution from some higher wave the η angular distribution is not flat, it is bowl shaped, see Figs. 4(a), 4(b), for production by π^- and K^-; this is expected from the replica nature.

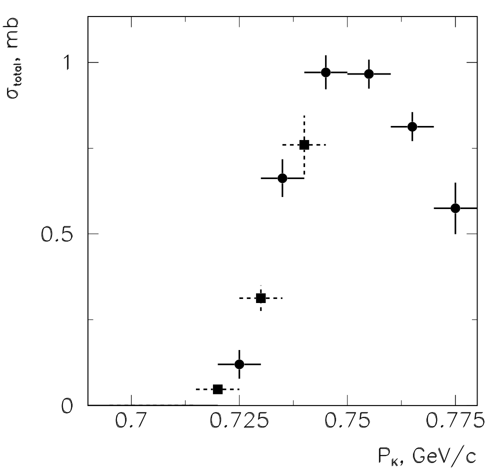

Fig. 2. The $\sigma_t(K^- p \to \eta\Lambda)$ excitation function measured with the Crystal Ball.

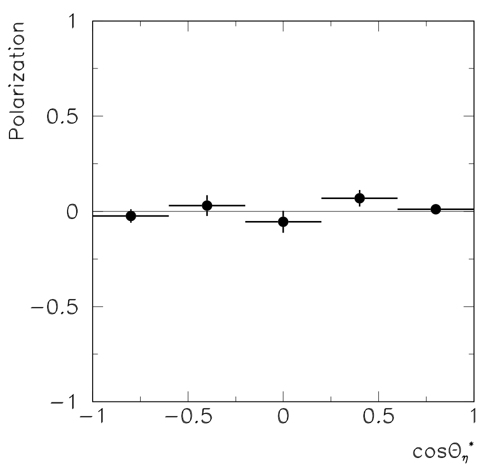

Fig. 3. Λ polarization in $K^- p \to \eta\Lambda$.

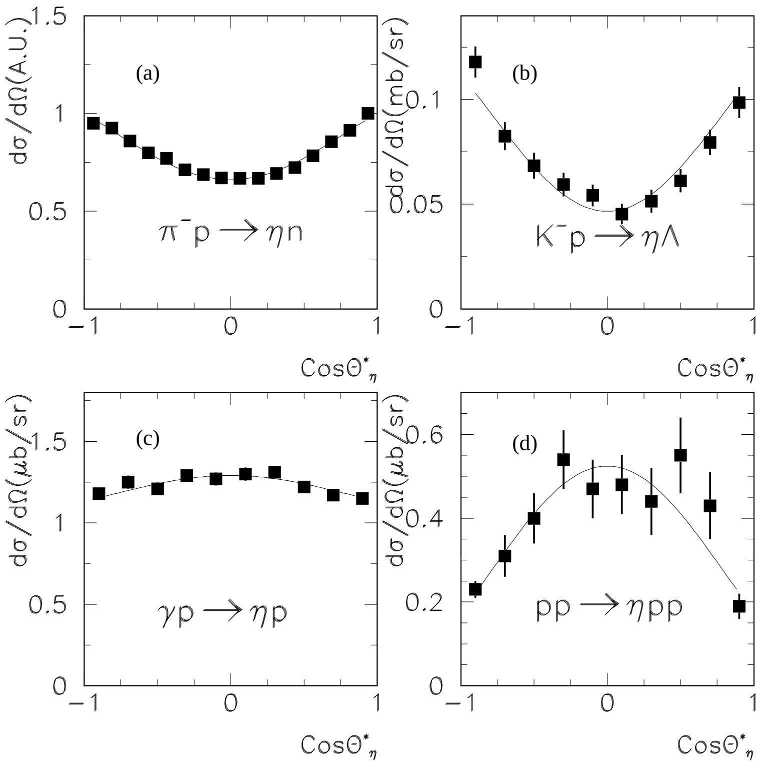

Fig. 4. Angular distributions in eta threshold production. The top row are Crystal Ball measurements, bottom left is from Ref. [7] and bottom right from Ref. [8].

Note that a bowl shape angular distribution is not a required feature of η production. Observe the dome shape which typifies $\gamma p \rightarrow \eta p$ and $pp \rightarrow pp\eta$, see Figs. 4(c), 4(d) [7, 8].

4.2. $K^- p \rightarrow \pi^0 \Lambda$

An example of a strangeness transfer reaction, from meson to baryon, is provided by the reaction $K^- p \rightarrow \pi^0 \Lambda$. The differential cross section at $p_k = 720$ MeV/c is shown in Fig. 5. The data and those of the next two reactions were obtained by N. Phaisangittisakul as a by-product of his thesis on radiative $K^- p$ interactions. The full analysis of this channel is under way at KSU, it is the thesis work of J. Olmsted. Typically the data samples which have been obtained in our Crystal Ball run are an order of magnitude bigger than in the older experiments [9]. The $\Lambda\pi^0$ final state is pure $I = 1$. There are several candidate intermediate states: the $\Sigma(1660)$ $P11$, which is a three-star state; the $\Sigma(1670)$ D_{13}, a four-star state, and the $\Sigma(1690)$ bumps.

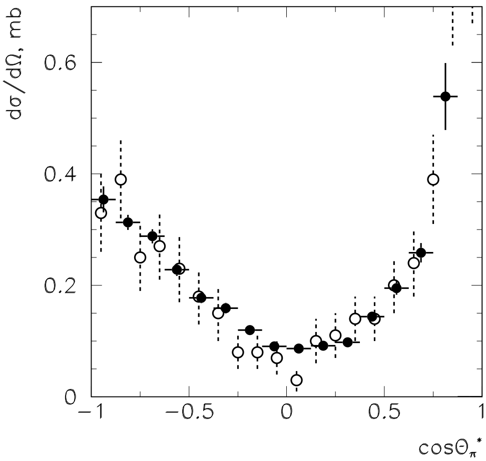

Fig. 5. $d\sigma/d\Omega(K^-p \to \Lambda\pi^0)$ at p_k = 720 MeV/c. The solid dots are the CB data, 6248 events. The open circles are data by Armenteros *et al.* Ref. [9], 600 events.

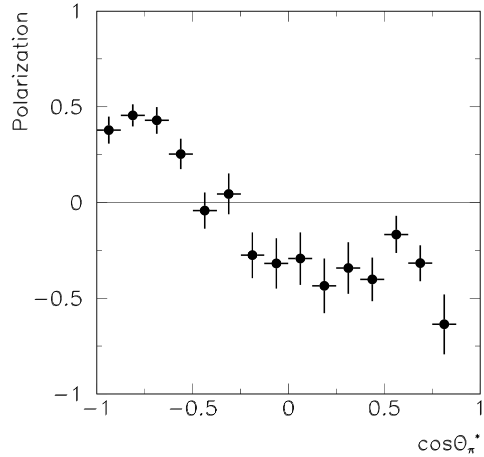

Fig. 6. Λ polarization in $K^-p \to \pi^0\Lambda$ at p_k=750 MeV/c measured with the Crystal Ball.

A coupled channel analysis including all our measurements together with the existing K^- elastic scattering and total cross section data are required to sort out the contributions of the different Σ^* states. The angular distribution of the Λ polarization at p_k =750 MeV/c is shown in Fig. 6. The Λ polarization varies from +0.5 to −0.3. These data are helpful in the partial wave analysis to resolve the Minami ambiguity. This bothersome ambiguity is the consequence of the invariance of the differential cross section of pseudoscalar meson–nucleon elastic scattering reactions to the interchange of all odd and even parity partial waves of the same I and J.

4.3. $K^-p \to \pi^0\Sigma^0$

The Σ^0 decays in 10^{-19} sec into $\Lambda\gamma$. The signature of the $\pi^0\Sigma^0$ final state is a 5 cluster event which forms uniquely two π^0's with different vertices and a "bachelor" photon with E_γ = 74 MeV in the Σ^0 center of mass. There are five constraints available for the analysis. This is ample to obtain a clean data sample. Shown in Fig. 7 are the CB data for $d\sigma(K^-p \to \pi^0\Sigma^0)$ at p_k = 750 MeV/c; we have included a sample of the older data by Armenteros *et al.* [9] obtained in a hydrogen bubble chamber for a comparison. The $\pi^0\Sigma^0$ final state is also isospin selective allowing only Λ^* states, this explains the difference between the shape of $d\sigma$ in $\pi^0\Lambda$ and $\pi^0\Sigma^0$ production.

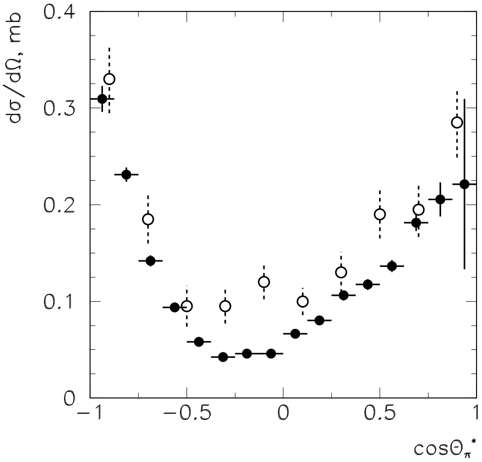

Fig. 7. $d\sigma/d\Omega[K^-p \rightarrow \pi^0\Sigma^0]$ at p_k=750 MeV/c. The solid dots are the CB data, 7150 events. The open circles are the data of Armenteros *et al.* [9], ~700 events.

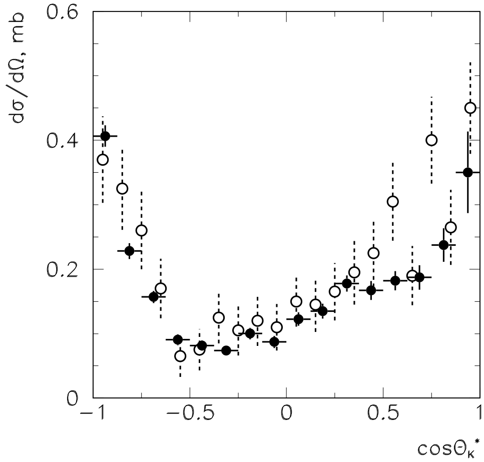

Fig. 8. $d\sigma/d\Omega[K^-p \rightarrow \overline{K}^0 n]$ at p_k=750 MeV/c. The solid dots are the CB data, 4765 events. The open circles are the data from Armenteros *et al.* [9], 730 events.

4.4. $K^-p \rightarrow \overline{K}^0 n$

The final state in K^-p charge exchange is detected in the CB as a four-cluster event, $\overline{K}^0 \rightarrow K^0_{\rm s}$ with BR=0.5 and $K^0_s \rightarrow 2\pi^0$ with BR=0.31. The K^0_s mean lifetime is 0.08 nsec, the decay distance is 2.7 cm. An example of the differential cross sections at p_k = 750 MeV/c is shown in Fig. 8. The charge exchange reaction involves two isospin amplitudes A_0 and A_1 as follows: $d\sigma(K^-p \rightarrow \overline{K}^0 n) \sim |A_0 - A_1|^2$, this complicates the analysis as both Λ and Σ states participate in the process. We expect a cusp in K^-p charge exchange at the opening of the η channel at p_k = 723 Mev/c.

4.5. $K^-p \rightarrow \pi^0\pi^0\Lambda$

An interesting example of SU(3)-flavor replication is seen in the Dalitz plots of $\pi^-\ p \rightarrow \pi^0\pi^0\ n$ and $K^-p \rightarrow \pi^0\pi^0\Lambda$ shown Fig. 9 at 750 MeV/c which have comparable kinematics. The $\pi^-p \rightarrow \pi^0\pi^0 n$ final state is characterized by a strong clustering of the $\pi^0 n$ invariant mass in the region of the Δ resonance, it is suggestive of the sequential reactions $\pi^-p \rightarrow N^* \rightarrow \pi^0\Delta \rightarrow \pi^0\pi^0 n$. The flavor replica of this is $K^-p \rightarrow \Lambda^* \rightarrow \pi^0\Sigma^0 \rightarrow \pi^0\pi^0\Lambda$. The $\Sigma(1385)$ is the decuplet replica of the $\Delta(1232)$. The similarity between the two Dalitz plots is remarkable. The main difference is that the $\Sigma(1385)$ has Γ = 36 MeV while the $\Delta(1232)$ has Γ = 120 MeV.

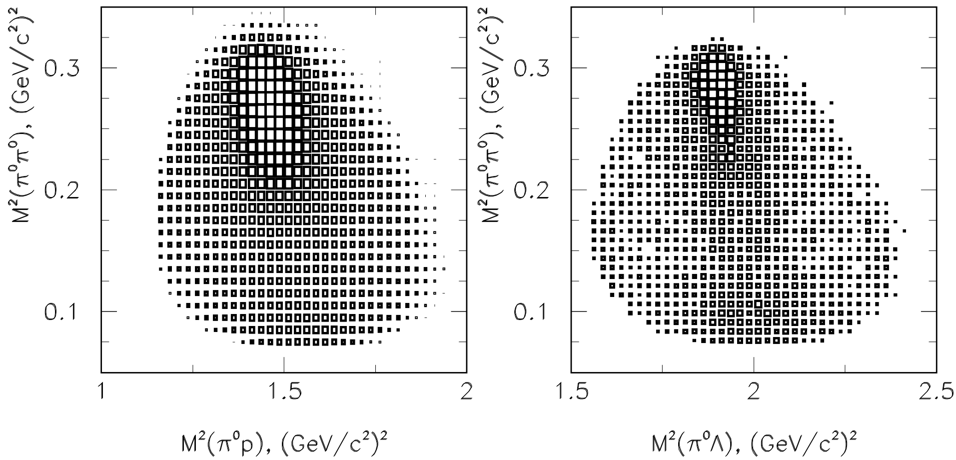

Fig. 9. Dalitz plot for $\pi^- p \to \pi^0\pi^0 n$ and $K^- p \to \pi^0\pi^0 \Lambda$ at 750 MeV/c measured by the Crystal Ball.

5. π^- induced reactions

With the Crystal Ball we measure all neutral final states at the same time. Our first experiment used beams up to 760 MeV/c π^- incident on a hydrogen target. The neutral final state particles that we detect with good efficiency are γ, $1\pi^0$, $2\pi^0$, $3\pi^0$, and η. The detection efficiency for neutrons above 50 MeV is about 35%.

5.1. $\pi^- p \to 3\pi^0$ (not η)n

At intermediate and low energies pions are produced by the decay of nucleon isobars and of σ and ρ mesons. $3\pi^0$ production takes place via $\pi^- p \to N^*$. At our energies the N^* is the $D_{13}(1520)$ and $S_{11}(1535)$ and the intermediate decay is $N^* \to \pi^0 P_{11}(1440)$ which is followed by $P_{11} \to \pi^0 \Delta(1230)$ or $P_{11} \to \sigma n$ where the σ is a quasi-particle that is a special feature of the strong S-wave π–π interaction. An advantage of measuring π^0's is that the intermediate state $\rho^0 \to \pi^0\pi^0$ is forbidden, this greatly simplifies the analysis of the $2\pi^0$ and even of $3\pi^0$ production reactions. The CB is especially suited to measuring three π^0's. Our preliminary results are given in Table I. Previous results on $3\pi^0$ production [10,11] are a factor 100 and more higher, this is suggestive of $\eta \to 3\pi^0$ contamination. Our $3\pi^0$ data imply that BR[$S_{11}(1531) \to \pi^0\ P_{11}(1440)$] $< 0.6\%$ and BR[$D_{13}(1520) \to \pi^0 P_{11}$] $< 0.2\%$ in agreement with the recent analysis of Manley [12].

TABLE I

$\sigma_{\rm total}(\pi^- p \to 3\pi^0 n)$ (not η).

p_{π^-} (MeV/c)	$\sigma_{\rm tot}^{3\pi^0}$ (μb)
653	2 ± 1
665	3 ± 1
675	4 ± 3
691	7 ± 3
704	13 ± 4
716	9 ± 7
750	27 ± 9

5.2. $\pi^- A \to \pi^0\pi^0 X$

Considerable attention is currently being given to the properties of hadrons in the nuclear medium [13, 14]. This is associated with the problem of "The origin of mass" [15]. QCD implies that a mere 2% of a nucleon's mass resides in the 3 current quarks while 98% is associated with the quark condensate. The latter is a manifestation of the breaking of chiral symmetry by the vacuum. Of special interest are the properties of the σ quasi-particle because it is considered to be the chiral partner of the π-meson. As such it is expected to have a decreasing mass when increasing the nuclear density. A simple estimate shows a decrease of 30% at ordinary nuclear density. We have used the CB to measure the $\pi^0\pi^0$ invariant mass spectrum produced by π^- on targets of CH_2, CD_2, C, Al and Cu. The results at $p_\pi = 408$ MeV/c are shown in Fig. 5. The low incident momentum was chosen because the outgoing pions have a small momentum so we can ignore in first order the $\pi^0 N$ final state interactions. We have also data at 750 MeV/c [16] where the final state πN interactions are stronger. The gross feature of both data sets are qualitatively similar. Our results for the $\pi^0\pi^0$ invariant mass are very different from the $\pi^+\pi^-$ data at 398 MeV/c reported by the CHAOS collaboration [17, 18] which shows a striking peak of 280 MeV in the $\pi^+\pi^-$ invariant mass, while our spectra are smooth. The latest development is an assertion [19] that these peaks are the consequence of the peculiar restricted acceptance of the CHAOS detector, however, no detailed Monte Carlo evaluation of the CHAOS acceptance is available. In a recent report [20] CHAOS has proposed to use the ratio of the $\pi^+\pi^-$ yields for different targets to probe medium modification. However, this is only meaningful for data that has been corrected for the acceptance of the detector which is known to vary with A because of the difference in the binding energies of the nucleons in the different complex nuclei.

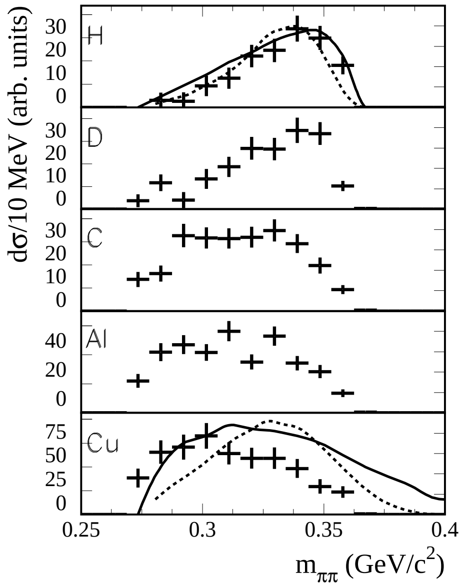

Fig. 10. Experimental results for the $2\pi^0$ invariant mass distributions for 408 MeV$/c$ incident π^- obtained for H, D, C, Al, and Cu targets, corrected for Crystal Ball acceptance. The vertical scale is in arbitrary units. The solid lines show the results of calculations made by Rapp [21], and the dashed line is the prediction by Vicente Vacas [22].

6. Tests of CP and C invariance in η decays

According to the Standard Model of electroweak interactions the small CP violation which is seen in neutral kaon decay originates in a phase of the C–K–M mass matrix of the six quark flavors. Tests of CP invariance in flavor conserving interactions are almost non existing. The decay mode $\eta \to 4\pi^0$ is forbidden by CP and P invariance, and it is a flavor conserving interaction. It's chief drawback is the smallness of the available final-state phase space. Experimentally this is a clean decay mode without serious background; even the potentially dangerous radiative decay, $\eta \to 4\pi^0\gamma$ is forbidden (by C-invariance). The experimental particulars which make $\eta \to 4\pi^0$ such an attractive decay is the unique signature of 8 photons which combine in only one way into $4\pi^0$ which combine into η. The η's are produced in the reaction $\pi^- p \to \eta n$ near threshold, they are nearly monochromatic and emerge in a very forward cone. This production type is referred to as "virtual tagging". In a 2 week run at the AGS with the CB we obtained a supply of $3.0 \times 10^7 \eta$'s. No candidate fulfilled our real event criteria. This results in the upper limit $\mathrm{BR}(\eta \to 4\pi^0) \leq 6.9 \times 10^{-7}$ at 90% CL. A comparison of this with the known width of the allowed decay $f_0(1500) \to 4\pi^0$ enables us to obtain an upper limit for the CP-violating amplitude with respect to the CP-conserving one: $A_{\overline{CP}}/A_{CP} \leq 2.3 \times 10^{-2}$, see Ref. [4].

The decay $\eta \to 3\pi^0\gamma$ is forbidden by C invariance, it is an isovector electromagnetic interaction. We have obtained a body of 18.9 $\times 10^6$ well-defined η decays. We did not find a signal in our sample of 7 cluster events above the background of $\eta \to 3\pi^0$ events with a split-off. This results in the upper limit at the 90% CL of BR$(\eta \to 3\pi^0\gamma) \leq 7.0 \times 10^{-5}$. For comparison note that BR$(\eta \to 3\pi^0) = 32\%$. Our result implies that the C-violating isovector amplitude is less than 3% of the C-conserving amplitude, which makes this the most accurate test of C in its category. After the discovery of CP violation in $K_{\rm L} \to \pi^+\pi^-$ decay the possibility of a new interaction, a C-violating electromagnetic interaction of hadrons, was proposed. Bernstein *et al.* [23] suggested a clear test, $\eta \to \pi^0\pi^0\gamma$ decay. Thus far no upper limit for this has been reported because a 4π-type detector is needed. The search is hampered by a large, intrinsic background which comes from $\eta \to 3\pi^0$ with a missing photon or overlapping clusters and from $2\pi^0$ production with a split-off photon. We have used the same sample of η decay employed above. No net signal was found above background. The upper limit is BR$(\eta \to 2\pi^0\gamma) \leq 4.2 \times 10^{-4}$ at 90% CL. Note that the C-allowed comparable decay for charged pions is BR$(\eta \to \pi^+\pi^-\gamma) = 4.8\%$. The comparison with the allowed strong decay $\rho^0 \to \pi^+\pi^-\gamma$ which has a width of 1.5 MeV implies that the ratio of the C-violating to C-conserving amplitude is $A_{\not{C}}/A_C \leq 6 \times 10^{-3}$. This is a test of an isoscalar and/or isotensor interaction. The latter is the exotic isotensor C- and T-violating interaction proposed originally by Sanda and Shaw [24].

Our final test of C-invariance is a new upper limit on $\eta \to 3\gamma$. Using our sample of 18.9 $\times 10^6 \eta$'s we obtain BR$(\eta \to 3\gamma) \leq 4.5 \times 10^{-5}$ at 95% CL. The existing upper limit [2] is 5.0×10^{-4} at 95% CL. The decay $\pi^0 \to 3\gamma$ for which the upper limit is 3.1×10^{-8} is not competitive as discussed by P. Herczeg [25]. Note that the decay rate depends on the 12th power of the meson mass [25], thus the sensitivity of $\eta \to 3\gamma = (m_\eta/m_\pi)^{12} \approx 3.0 \times 10^7$ better than $\pi^0 \to 3\gamma$.

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