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UCLA PARTICLE AND NUCLEAR PHYSICS RESEARCH GROUP

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Synopsis

The research programs of the UCLA Particle and Nuclear Physics Research Group, the research objectives, results of experiments, the continuing activities and new initiatives are presented. The primary goal of the research is to test the symmetries and invariances of particle/nuclear physics with special emphasis on investigating charge symmetry, isospin invariance, charge conjugation, and CP. Another important part of our work is baryon spectroscopy, which is the determination of the properties (mass, width, decay modes, etc.) of particles and resonances. We also measure some basic properties of light nuclei, for example the hadronic radii of ^3H and ^3He . Special attention is given to the eta meson, its production using photons, electrons, $\pi^\pm$, and protons, and its rare and not-so-rare decays.

In Section 1, the physics motivation of our research is outlined. Section 2 provides a summary of the research projects. The status of each program is given in Section 3. We discuss the various experimental techniques used, the results obtained, and we outline the plans for the continuing and the new research. Details are presented of new research that is made possible by the use of the Crystal Ball Detector, a highly segmented NaI calorimeter and spectrometer with nearly 4π acceptance (it was built and used at SLAC and is to be moved to BNL). The appendix contains an update of the bibliography, conference participation, and group memos; it also indicates our share in the organization of conferences, and gives a listing of the colloquia and seminars presented by us.

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PROGRAM I: *Charge Symmetry and Isospin Invariance*

I-1 Introduction

Charge symmetry and isospin invariance are profound contributions to physics that originated in nuclear physics. The seminal work of Yang and Mills on isospin and gauge transformations is a good example. The modern story of charge symmetry, CS, and charge symmetry breaking, CSB, is one of the (rare) successes of QCD in nuclear physics. CS started as the equality of the nn and pp interactions. When particle physics came along, it was expanded to the equivalence of the isospin partners.

CS is the first case of a (slightly) broken symmetry. The breaking is seen in the mass splitting, for instance, of the n - p and $K^0 - K^+$ doublets. Charge symmetry breaking is due to the Coulomb interaction and to a less familiar "intrinsic source." QCD relates CS in nuclear physics to CS in particle physics, and it identifies the up-down quark mass difference $\delta m(d-u)$ as the source of intrinsic CSB. QCD ascertains that the interaction between all *massless* quarks is the same, irrespective of whether they are u , d , s , c , or b quarks. In the real world, this *flavor independence* of the strong interaction is not maintained since quarks are particles which have different masses. The effective mass of the u and d quarks is about the same; consequently, the primordial flavor independence of massless QCD is preserved for u and d quarks and shows up as charge symmetry. In modern terminology, CS is defined as the invariance of the strong interaction under the interchange of the up and down quarks. All CSB is a consequence of the up-down quark mass difference and the small electromagnetic correction stemming from the difference in electric charges and magnetic moments of the up and down quarks. The well-established cases of CSB in particle and in nuclear physics have all been explained quantitatively using the value $\delta m = 3$ MeV [1,2].

One of the triumphs of modern theoretical nuclear physics is the successful incorporation of the intrinsic CSB, which originates in the up-down quark mass difference, into nuclear potentials. This is accomplished via the phenomenon of meson mixing, specifically by $\rho^0 - \omega$ and $\pi^0 - \eta$ mixing. It is described as follows. The contribution to the QCD Hamiltonian density H_m that depends on the quark masses is

$$H_m = m_d d\bar{d} + m_u u\bar{u} + \dots \quad (1)$$

The quark composition of the physical π^0 and η mesons is

$$|\pi^0\rangle = \frac{1}{\sqrt{2}} |u\bar{u} - d\bar{d}\rangle, \text{ and } |\eta\rangle = \frac{1}{\sqrt{3}} |u\bar{u} + d\bar{d} - s\bar{s}\rangle. \quad (2)$$

The matrix element for $\pi^0 - \eta$ mixing is then

$$\langle \pi^0 | H_m | \eta \rangle = \frac{1}{3} \sqrt{6} (m_u - m_d). \quad (3)$$

Similarly, for $\rho^\circ - \omega$ mixing we have that

$$\langle \rho^\circ | H_m | \omega \rangle = (m_u - m_d). \quad (4)$$

$\rho^\circ - \omega$ mixing has been studied in great detail. Persuasive evidence [3,4] has been found in measurements of the ratio r ,

$$r \equiv d^2\sigma(\pi^- d \rightarrow \pi^+ \pi^- nn)/d^2\sigma(\pi^+ d \rightarrow \pi^- \pi^+ pp). \quad (5)$$

This r deviates very much from the CS value of 1.0 in the energy region where the ω channel is opening. In various nuclear physics measurements of CSB, it appears that $\rho^\circ - \omega$ mixing carries the most weight.

$\pi^\circ - \eta$ mixing has only been observed in particle physics in rare decays such as $\eta' \rightarrow \eta \pi^\circ \pi^\circ$ or $\psi' \rightarrow \psi \pi^\circ$ [1]. There is no direct evidence in a nuclear reaction. It may be argued that the large difference between the physical masses of the π° and the η is to blame for this. Our experimental approach has therefore been to choose a case where the energy is sufficiently high for the on-shell transition $\eta \leftrightarrow \pi^\circ$.

There are no experimental investigations of CS involving an η -nuclear system. What makes this so interesting is the fact that the S-wave $\eta - N$ interaction is attractive; this stands in contrast to the (πN) system which is repulsive in the S-state. The process $\eta N \rightarrow \pi N$ is very exothermic and it is expected that η -nuclear interactions in the final state reduce the η production compared to models employing the impulse approximation. Yet the opposite is found experimentally; for example, the measured value for $d\sigma(\pi^- {}^3\text{He} \rightarrow \eta {}^3\text{H})$ is 2-3 times larger than the impulse approximation calculation [3]. It is expected that CSB is enhanced in an η -nuclear system by on-shell $\pi^\circ - \eta$ mixing.

Until quite recently, the role of the η meson in nuclear physics was ignored. This aspect must be reassessed in light of the startling results of recent Saturne experiments [4,5] on η production in nuclear reactions near threshold; it was found that the cross sections are extraordinarily large, e.g., $\sigma_t(np \rightarrow d\eta) \simeq 0.3$ mb. It is important to investigate the validity of CS involving the η -nuclear system where large CSB effects are possible.

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I-2 A New Test of Charge Symmetry in Eta Production on Deuterium (AGS Exp. #890)

As part of the η program at the AGS, we are planning to perform a test of charge symmetry by measuring the following ratios of production and scattering cross sections:

$$R_\eta = \frac{\sigma(\pi^+ d \rightarrow pp\eta)}{\sigma(\pi^- d \rightarrow nn\eta)};$$

$$R_\pi = \frac{\sigma(\pi^+ d \rightarrow pp\pi^0)}{\sigma(\pi^- d \rightarrow nn\pi^0)};$$

$$R_{el} = \frac{\sigma(\pi^+ d \rightarrow \pi^+ d)}{\sigma(\pi^- d \rightarrow \pi^- d)};$$

$$R_{\eta\pi} = \frac{R_\eta}{R_\pi}, \quad R_{\eta el} = \frac{R_\eta}{R_{el}} \text{ and } R_{\pi el} = \frac{R_\pi}{R_{el}}.$$

The superratios $R_{\eta\pi}$, $R_{\eta el}$, and $R_{\pi el}$ are measured instead of the simple ratio R_η to eliminate uncertainties associated with the pion beam flux. Charge symmetry, CS, requires that the three superratios are equal to 1.0 for all incident pion energies and for all scattering conditions, after minor adjustments have been made to compensate for the n-p mass splitting and for the Coulomb interaction. A large violation of CS, perhaps 20-30%, is expected at the opening of the η channel as a result of $\pi^0 - \eta$ mixing. At all incident energies, there are smaller CS violations due to the difference in the $nn\eta$ and $pp\eta$ coupling constants and nn and pp scattering lengths.

The technique for measuring R_η and R_π uses a spectrometer to detect the 2γ decay mode of the π^0 and η . The reconstructed invariant mass identifies η and π^0 production. Since this method is independent of the charge of the final state nucleons, it has just small systematic errors associated with identifying the production reaction. The pion flux is monitored by counters that measure πp and πd elastic scattering. The former will be used to provide the normalization for each pion beam polarity; the latter is used to provide the relative normalization R_{el} between the two beam polarities.

A 300 hour test run took place in the summer of 1993 to demonstrate the technical feasibility of the experiment and to optimize the detector design. The results of this run are being analyzed. The full measurement will take place in the spring of 1994. Figure I-2-1 shows the experimental setup for the test run consisting of a beam spectrometer, the LANL η spectrometer, and 7 pairs of beam monitors. Because of availability, a CD_2 target was used rather than the liquid D_2 target which is planned for the actual experiment. The carbon introduced a substantial background which had to be subtracted.

The beam spectrometer utilizes the last bending magnet in the beam line, **BM02**, for analyzing the momentum of each beam particle tagged by scintillators **S1** and **ST**. There are two $\vec{E} \times \vec{B}$ separators just upstream of **BM02** to deflect particles which have the wrong velocity from the nominal beam direction. A mass slit is located between the separators and **BM02** allowing only the undeflected particles to enter **BM02**. **S1** tags these particles. They then pass through a scintillator hodoscope and drift chambers before being bent by **BM02**. There are quadrupole magnets before and after **BM02** for final beam focusing. The beam passes through three pairs of **X,Y** drift chambers and the target scintillator **ST** to determine the final beam direction for each particle. The flight path between **S1** and **ST** is approximately 5 m, and time-of-flight (TOF) can be used to identify pions from protons or kaons. However, the resolution is not sufficient to separate muons or electrons in the beam, and these provide the major beam contamination problem. The beam spectrometer typically yields a resolution of $\sim 0.3\%$ and the momentum spread in the beam ($\Delta p/p$) is typically 2-3%. Figure I-2-2 shows the beam profile as well as the angular and momentum dispersions at the target with comparisons to the TURTLE simulations of the beam tune. The present rate limit of the beam spectrometer is about 5×10^6 particles/spill or about 1.6 MHz instantaneous, due to the drift chambers used. Typical beam rates during the test run were $\sim (2 - 4) \times 10^6$ particles/spill. While such rates are more than adequate for the charge symmetry experiment, higher rates will be needed for the rare η decay program. During the test run, low tracking efficiency was observed. Presumably, much of this was due to multiple tracks which could not be resolved. Faster drift chambers (which will be available), better time resolution, and a second hodoscope upstream of **BM02** will significantly improve this situation.

Electron contamination of the beam had been seen in a beam study run the previous summer, and so we wanted to monitor this in the test run. A scintillator was placed in the beam just in front of the beam stop approximately 8 m from **ST**. This gave a sufficient TOF measurement to distinguish the electron component. Beam studies conducted during the test run indicated that between 25-50% of the beam consists of electrons. This contamination can be significantly reduced by placing a thin lead absorber at the mass slit upstream of **BM02** without seriously degrading the quality of the beam.

The LANL η spectrometer, which has already been employed for measuring η production at LAMPF, was used to detect the 2γ decay. Figure I-2-3 shows a schematic of the two γ detectors which make up the spectrometer. Normally, the γ 's are converted in the active BGO converter, then the shower is tracked in the wire chambers and the energy measured in the NaI counters. The forward scintillators provide a charged particle veto, and the scintillator plane in front of the NaI counters is a fast trigger for the shower. Typical rates in the NaI counters were ~ 2000 counts per 10^6 beam particles. Figure I-2-4 shows a 2γ event in the NaI arrays associated with an invariant

mass greater than $400 \text{ MeV}/c^2$.

One question we wanted to address during this test run was whether the spectrometer could be run in a mode using only the NaI counters to detect the γ rays. Since the NaI is 16 radiation lengths (r.l.) thick, and the BGO is only 1 r.l. thick, this meant a factor of ~ 5 increase in efficiency for the spectrometer. The angular resolution of the spectrometer would be degraded, but since the opening angle of the η is large ($\sim 130^\circ$), the invariant mass is relatively insensitive to the angular resolution. By triggering on the NaI detectors only, the converted photon data is a subset of the raw data and we could compare the performance of the two modes directly. Trigger rates could be controlled by setting high energy thresholds on each arm. Figure I-2-5 shows the effect on the invariant mass spectrum when cuts are placed on the left, right NaI arrays. Typical event rates were about 20 counts per 10^6 beam particles. Figure I-2-6 shows the invariant mass spectra from $\pi^\pm$ on CH_2 ($p_\pi = 720 \text{ MeV}/c$) with the energy cut of 225 MeV shown in the previous figure and the resulting subtracted spectrum. A Carbon and empty target subtracted spectrum is also shown for comparison. The comparable yields indicate that our relative normalization is reasonable. An absolute normalization of the beam has not yet been done. Figure I-2-7 shows the raw as well as carbon and empty target subtracted spectra for π^+ on CD_2 at $p_\pi = 720 \text{ MeV}/c$. The yield is approximately 20% of that for π^-p at the same beam momentum. The resolution of the invariant mass is limited by the energy resolution of the NaI counters. A comparison of the converted photon data to the nonconverted has not yet been completed.

The π -p beam monitor (πPM) consists of a pair of scintillator detectors placed at 50° to the target scintillator. This is the symmetric scattering angle for the pion and proton, so the detectors should have identical spectra. The monitor is then less sensitive to systematic errors due to alignment or beam movement. All of the beam monitor detectors consist of a 2" photomultiplier tube which views the rear face of a $20 \times 20 \text{ cm}^2$ square of plastic scintillator 1 cm thick. An aluminized mylar cone is used to form an air light guide. Figure I-2-8 shows a two dimensional plot of pulse height versus TOF for both of the πPM detectors. The pion and proton loci are clearly distinguished. The plot of one pulse height versus the other indicates the only background is a small contribution, presumably from 2π events. These monitors typically yield a few thousand counts each for protons with an integrated flux of $\sim 2 \times 10^7$ particles and appear to be insensitive to the electron contamination; this has still to be investigated more carefully. The π -d monitors (πDM) consists of 6 pairs of scintillator detectors identical in construction to the πPM detectors. Two pairs are located at the symmetric scattering angle of 55° for πd elastic scattering and four pairs are arranged to detect forward scattered deuterons at $\theta_{lab} = 15^\circ$ and the backscattered pions at $\theta_{lab} = 140^\circ$. The elastic cross section is small at the symmetric angle, but presumably has less background than the 15° detectors. Pulse height and time of flight can be used to identify the deuteron signal just as in the case of the πPM . Backgrounds do not appear to be a problem with either geometry.

The analysis of these detectors is still preliminary, and rates have yet to be determined.

A second goal of this test run was to study the feasibility of tagging η production at the AGS using the neutron for the reaction $\pi^- p \rightarrow n\eta$ and the protons from the reaction $\pi^+ d \rightarrow pp\eta$. Tagging is important for future experiments involving the study of rare or forbidden η decays, so some time was spent studying the possible background problems associated with tagging η at the AGS.

Six neutron counters from UCLA were set up downstream of the target (~ 6 m and 2.5 m) to detect neutrons from the first reaction. These are plastic scintillation counters $3.5 \times 9.75 \times 10$ in³ ($W \times H \times D$) with two photomultiplier tubes for each counter. Three counters are mounted together to form a $10.75 \times 9.75 \times 10$ in³ block. Two such blocks were mounted on either side of the beam in the scattering plane defined by the spectrometer arms. The trigger for neutron tagging studies required a coincidence between a beam pion trigger generated by ST and any one of the neutron counters. Analysis of these data is under way.

The neutron counters were placed approximately 50 cm from the target for the detection of protons from the second reaction, $\pi^+ d \rightarrow pp\eta$. The neutron counters now acted as total energy counters for the protons and the neutron counter vetos became dE/dx counters. The trigger required only the NaI and a beam track. Figure I-2-9 shows a typical $\Delta E - E$ plot for one neutron counter indicating a clear proton locus and the corresponding effect on the invariant mass spectrum when a loose cut is made requiring a proton in one of the neutron counters. No neutral particle requirement has been made on the spectrometer arms at this point, so the effect of proton tagging is clearly evident. Once neutral particles are required, the effect with and without proton tagging on the invariant mass spectrum is seen in Fig. I-2-10. The statistics are poor due to the relatively small acceptance of the neutron counters to the total proton phase space, about 10% of the spectrometer acceptance for η production. These data clearly indicate that we can identify the protons associated with η production from deuterium with relatively minor background when combined with the requirement of a restrictive spectrometer trigger. We intend to spend some time next spring further exploring the capabilities of this mode of tagging.

Preliminary results indicate that both major aspects of the experiment, namely the η spectrometer and the beam monitors, are functioning satisfactorily. We foresee no major problem with running the experiment in the spring of 1994. Presently, the liquid D_2 target is being designed, a new beam tune has been developed which will significantly reduce the momentum acceptance of the beam, and the data acquisition system is being upgraded to improve the throughput of the system.

Fig. I-2-1. Experiment layout of the test run for Exp. 890 at the AGS. Blowups show details of the beam monitor arrangement and the spectrometer elements. The neutron counters were placed at two different locations during the run, 5.3 m and 2.5 m downstream of the target.

Fig. I-2-2. Comparison of the test run data (line) with the TURTLE prediction (circles) for the pion beam on the C-8 line at the AGS. $\frac{\Delta P}{P}$ is typically 3% FWHM. Resolution for an individual measurement is typically 0.3% FWHM.

Fig. I-2-3. Exploded view of the η spectrometer. Drift chambers were used instead of MWPC's, and the first plane of scintillators is the veto counters. The NaI counters are 16 r.l. and the BGO 1 r.l. thick.

Fig. I-2-4. Lego plot of an η event in the NaI counters showing the individual counters hit and the energy deposited in each. Orientation is such that the front of each array is being viewed.

Fig. I-2-5. Comparison of the Invariant Mass Spectra obtained with different values of the photon energy cut on both spectrometer arms. The majority of the data consists of a low energy photon in at least one of the arms.

I-2-8
720 MeV/c π^-p η Production

Fig. I-2-6. Eta production results for π^-p from CH_2 using two different subtraction techniques. The good agreement between the two methods indicates the beam normalization by the beam monitors is working, despite the electron contamination.

$\pi^+d \rightarrow \eta pp$ at 720 MeV/c

Fig. I-2-7. Eta production from π^+d on CD_2 with Carbon target and empty target subtracted.

Fig. I-2-8. Plots of the pulse height versus TOF for the two πp beam monitors PIPUP and PIPDOWN. The lower plots are the TOF only. These data show excellent separation of the elastically scattered pions and protons. Beam normalization is accomplished by counting the protons in each counter using an ADC cut to reject the pions.

Fig. I-2-10. Comparison of Invariant Mass spectra for $\pi^+ d$ using CD_2 with and without tagging but requiring neutrals in the spectrometer arms. Eta production is clearly evident above 500 MeV/c^2 in the tagged spectrum.

Fig. I-2-9. Tagging protons in π^+d using CD_2 . (Top) Plot of ΔE vs. E in which the neutron counter veto is being used as a ΔE counter and the neutron counter is an energy counter. A proton band is clearly evident. (Bottom) Invariant Mass spectra with (right) and without (left) requiring proton cuts in the neutron counters. Trigger did not require neutrals in the spectrometer.

I-3 The Superratio and the Two Standard Ratios of $\pi^\pm$ Scattering on ^3H and ^3He

Several years ago we pioneered a series of tests on nuclear charge symmetry by measuring the ratio of π^+ and π^- scattering on the isospin doublet ^3He and ^3H . Particularly useful is the superratio, R , where

$$R \equiv \frac{d\sigma(\pi^+ ^3\text{H}) \cdot d\sigma(\pi^- ^3\text{H})}{d\sigma(\pi^+ ^3\text{He}) \cdot d\sigma(\pi^- ^3\text{He})}.$$

The great merit of the superratio comes from the fact that it avoids the measurement of the absolute pion beam fluxes. These are notoriously difficult to determine, rendering the accurate measurement of the standard charge symmetry ratios r_1 and r_2 very difficult,

$$r_1 = d\sigma(\pi^+ ^3\text{H})/d\sigma(\pi^- ^3\text{He}) \quad \text{and} \\ r_2 = d\sigma(\pi^- ^3\text{H})/d\sigma(\pi^+ ^3\text{He}).$$

Charge symmetry requires that R , r_1 , and r_2 are equal to 1.0. All three ratios are sensitive to small differences in the wavefunction of ^3H and ^3He that are far beyond the sensitivity of the current electron scattering experiments.

The above type of CS experiments requires the use of a large tritium target, which we have arranged at LAMPF. In close collaboration with the technical staff of Los Alamos National Laboratory, we developed two kinds of gaseous targets. The first tritium target was a sealed spherical container, 12 cm in diameter, with 0.06 cm thick walls made of stainless steel and covered with a gold flash to minimize diffusion through the target wall. It contained 30 kCi at 13 atm and served very well for the pioneering experiment LAMPF #546. Based on the experience gained, a larger target was designed; it had a cylindrical shape, was made of aluminum and had 0.18 cm wall thickness. It was operated at 30 atm and contained 180 kCi tritium. With this target, we have performed Exps. #905, 1032, 1064, and 1155.

A large amount of $\pi^\pm$ scattering data from these two ^3H and an identical ^3He targets have been obtained. The major portion of the elastic scattering results have been analyzed and published, Refs.[1-3]. An important part of the analysis of the latest experiment on backward angle scattering has been done at GWU, culminating in a Ph.D. thesis, Ref. 4. An example of our elastic cross section data is shown in Fig. I-3-1. The ratios R , r_1 , r_2 , see Figs. I-3-2 and I-3-3, show a marked deviation from the CS prediction 1.0; the effect is particularly pronounced in the angular region of the non-spin-flip-dip (NSF-dip) near 68° . The results on the superratio have led to a new analysis of the scattering radii of ^3H and ^3He by Gibbs and Gibson [5]. They have obtained a CS violating difference between ^3H and ^3He of $\delta_e = -0.030 \pm 0.010$ fm for the even nucleon radii, and $\delta_o = 0.038 \pm 0.007$ fm for the odd nucleon radii, or about a 2% difference; this shows the great sensitivity of the superratio technique.

We are now engaged in analyzing inelastic data close to the break-up energy. A paper has been submitted recently on inelastic data of Exps. #905 and #546. A comparative study of inelastic pion with inelastic electron scattering data for ^3H and ^3He , which has been measured in the same kinematical region at Bates, is in progress.

Our phenomenological analysis shows a direct relation between the matter form factors explored in pion scattering and the nucleon-transition form factors found in reactions such as $pd \rightarrow ^3\text{He} \pi^0$ and $\pi^- ^3\text{He} \rightarrow \eta ^3\text{H}$. We are investigating the close correlation that we discovered with the electromagnetic form factors measured in electron scattering.

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Fig. I-3-1 The differential cross section for $\pi^- {}^3\text{H}$ and $\pi^+ {}^3\text{He}$ elastic scattering at $T_\pi = 180$ MeV. Open squares: Exp. #546, Ref. [1]; crosses: Exp. #905, Ref. [2]; open diamonds: Ref. [3]; filled squares: Ref. [4]. The solid line is the calculation by Gibbs and Gibson, Ref. [5].

Fig. I-3-2 The simple ratios r_1 and r_2 .

Fig. I-3-3 The superratio R .

PROGRAM II: η Decays

II-1 Introduction

The Standard Model (SM) [1,2] of particle physics is now the standard by which new theories and ideas are evaluated. The SM enjoys the successes of the Electroweak Theory as well as the Quark Model; this is discussed in Refs. [3-5].

There are few physicists who believe that the SM is the ultimate particle physics theory for reasons of principle and practice. The SM in its present three-family format has no room for unification of the strong, electromagnetic, and weak interactions with gravity. There is a glaring inconsistency between quarks and leptons since lepton family number is conserved, while quark family number is not. CP violation is not understood beyond the phenomenological level. A burning problem for the SM concerns the fact that it requires too many input parameters. No reason is provided for the number of families, nor is any model known for the mass scale of the quarks and leptons. No theory exists of quark confinement in the nuclear medium.

To test the SM, there are basically two types of experiments:

1. Searches for new particles. One can search for the vital missing particles, the t -quark and the Higgs bosons, or one can search for new types of particles that do not fit in the present SM such as magnetic monopoles, sparticles, or leptoquarks.
2. Searches for new interactions. This may be accomplished via precision measurement of rare decays, or by the discovery of a forbidden decay mode of an elementary particle. For instance, one can search for a new lepton-family-violating interaction in the "forbidden decay" $\eta \rightarrow \mu e$. One may also search for a new, non Cabibbo-Kobayashi-Maskawa CP-violating interaction via an enhancement of the rare decay $\eta \rightarrow \pi^+ \pi^-$. In the SM this can have a branching ratio (BR) $\leq 10^{-10}$ in case there is a strong CP violation governed by the θ parameter.

The rare and forbidden decays of the eta meson offer some unique possibilities for testing the SM. Eta decays have been neglected so far for lack of a suitable source of tagged etas; we shall return to this aspect later. The advantage of the eta meson is the fact that it has the quantum numbers of the vacuum

$$J = Q = I = s = c = b = B = L_i = 0,$$

where J is the spin, Q is the electric charge, I = isospin, s = strangeness, c = charm, b = beauty, B = baryon number, and L_i = lepton family number. The G-parity and charge symmetry are both +1 and so is charge conjugation; the intrinsic parity is -1. Except for having negative parity, the η appears to be "massive vacuum." Thus, η decays concern transitions without a change of flavor. This contrasts with the popular studies of neutral kaon decays such as $K_L \rightarrow \mu^+ \mu^-$ which is a $\Delta S = 1$ transition. Thus, new transitions can be investigated that are not accessible in decays of the K-meson

or muon. The disadvantage of the eta is the short half-life, a factor $\sim 10^{10}$ smaller than for the K-meson, which can make it less competitive. Table II-1-1 shows various interesting decay modes of the η -meson, the physics laws that are being tested, the expected branching ratio in the SM, and the current experimental limit. In section II-5, we discuss some particularly interesting eta-decay modes that become accessible with the use of the Crystal Ball Detector. This device is described in some detail in section V-1.

II-2. The Not-So-Rare Decay $\eta \rightarrow \gamma\gamma$ (LNS Experiment 258)

The SPES2 eta tagging facility allows for the first time a direct measurement of the branching ratio

$$\text{BR}(\eta \rightarrow \gamma\gamma) \equiv \frac{\Gamma_{\eta \rightarrow \gamma\gamma}}{\Gamma_{\eta \rightarrow \text{all}}} \quad (1)$$

The $\text{BR}(\eta \rightarrow \gamma\gamma)$ is a basic quantity in several respects:

1. Together with the partial width $\Gamma_{\eta \rightarrow \gamma\gamma}$ (measured in two-photon η production or in Primakov production), it determines the total width of the η meson for which no direct measurement has been shown feasible; ($\Gamma_{\eta \rightarrow \text{all}} = 1.19 \pm 0.11$ keV). [1]
2. Some electromagnetic decay rates such as $\Gamma_{\eta \rightarrow \ell^+\ell^-}$ can be calculated with reasonable accuracy relative to the $\eta \rightarrow \gamma\gamma$ decay rate. Then, the $\text{BR}(\eta \rightarrow \gamma\gamma)$ is needed to verify that the measured branching ratios for the electromagnetic decays are consistent with the calculations.
3. In many processes, the cross-sections for η production are measured by identifying the η meson via its two-photon decay. The results are then inversely proportional to the $\text{BR}(\eta \rightarrow \gamma\gamma)$.

We are performing a direct, 1-2% precision measurement of the $\text{BR}(\eta \rightarrow \gamma\gamma)$. The systematic errors are quite different than in the previous indirect measurements. Figure II-2-1 shows the experiment layout. The η mesons were produced in the reaction $p d \rightarrow {}^3\text{He} \eta$, where the protons have a kinetic energy of 1.5 MeV above threshold in the laboratory reference frame. The 6mm thick liquid deuterium target was arc-shaped in order to reduce the amount of target and target wall materials between the $\eta \rightarrow \gamma\gamma$ vertex and the photon detectors. Ideally, the target would have been cylindrical; however, this design would have been too expensive. Using $\sim 10^{10}$ protons per 0.47s beam spill (1.1s beam cycle period), we produced roughly 30 η 's per spill. The recoil ${}^3\text{He}$ is identified and its vector momentum is measured by the SPES2 spectrometer following the same procedures as in our previous experiment, LNS Experiment 198 ($\eta \rightarrow \mu^+\mu^-$), as described in [2]. The η tag, *i.e.* the selection of $p d \rightarrow {}^3\text{He} \eta$ with cuts applied to the measured ${}^3\text{He}$ momentum, makes possible an accurate measurement of the number of η 's produced. Two calorimeters, placed at $\pm 65^\circ$ w.r.t. the beam axis, measured the photon energies and directions. The calorimeters, on loan from the Paul Scherrer Institute (PSI), each consist of 61 hexagonally-cut BGO scintillation counters, each measuring $25.8\text{cm}^2 \times 20$ cm long (17.8 radiation lengths). Each calorimeter was placed within a box, which served to thermally isolate it; heaters controlled by thermostats maintained the BGO calorimeters at a stable temperature, which was necessary because BGO scintillation light output is highly temperature-dependent. In a crude, preliminary analysis we were able to obtain a photon energy resolution of $\sim 13\%$ FWHM. A lead collimator placed in front of one of the calorimeters (see Figure II-2-1) defines the detector acceptance. The non-collimated calorimeter accepted the other photon from $\eta \rightarrow \gamma\gamma$ which is in coincidence with the collimated arm. To account for the angular and energy distributions of the η , the non-collimated calorimeter was closer to the target, subtending a larger solid angle than the collimated calorimeter. The distances between the calorimeters and the target ($d(C)$ and $d(NC)$ in Figure II-2-1) were adjustable: $d(C)=770-960$ mm and

$d(NC)=540-710$ mm for the collimated and non-collimated calorimeters, respectively. A thin veto counter on the collimated arm suppresses charged-particle background.

We performed a test run in May, 1993, to study systematic uncertainties and the rate of accidentals. We estimate that the probability of pile-up which contributes more than 5 MeV to the measured energy of a photon is $< 6\%$ in the non-collimated calorimeter, and $< 3\%$ in the collimated calorimeter.

In June, 1993 we successfully took data; the experiment is currently in the data analysis stage. To better understand the systematic uncertainty introduced by the collimator edge effects, we took data using each of 3 interchangeable collimators of different acceptance. During a portion of the experiment, we placed a BGO detector next to the collimator such that this detector defined part of the acceptance of the collimator aperture. This detector served as an active collimator counter. To better understand the systematic uncertainty due to energy leakage out the side of the calorimeters, we varied the distance between the target and the calorimeters. Table II-2-1 lists the various configurations tested.

Between beam spills, we acquired cosmic rays which we used to calibrate the BGO counter amplitudes relative to each other. Figure II-2-2 shows the calorimeter profile for a typical cosmic ray event and a typical $\eta \rightarrow \gamma\gamma$ event. The relative amplitude calibration is accomplished by aligning the peaks of the cosmic ray spectra of the individual BGO counters to the same (though arbitrary) value, as shown in Figure II-2-3.

Light from pulsed LED's generated artificial signals in each BGO counter. The resulting "LED events" are useful for monitoring the short-term stability of the PM tube gain. Longer term gain stability can be verified using the cosmic ray events.

A preliminary analysis of one run (approximately $1\frac{1}{2}$ hours of data acquisition taken during the May beam time) yields a clean sample of $624 \pm 25 \pm 30$ $\eta \rightarrow \gamma\gamma$ events (Figure II-2-4),

$$BR(\eta \rightarrow \gamma\gamma) = 0.38 \pm 0.02 \pm 0.04$$

The full data analysis is required in order to reach the desired 1-2% experiment precision. Our tentative analysis plan includes the following:

- Adjustment of various parameters, ADC gains and TDC offsets. Calibration of ADC gains of the BGO counters, using cosmic ray events and $\eta \rightarrow \gamma\gamma$ events. Correction for gain fluctuations of the PMs, by using the LED event data.
- Testing the consistency of various scaler counts for each beam cycle.
- Analysis of the $p d \rightarrow {}^3\text{He} \eta$ events, which provides the number of η 's produced. Verification that the ${}^3\text{He}$ spectra exhibit the same behavior for both the $p d \rightarrow {}^3\text{He} \eta$ events and the $\eta \rightarrow \gamma\gamma$ events.
- Definition of clusters of BGO counters which respond to the electromagnetic showers induced by the photons from $\eta \rightarrow \gamma\gamma$. Reconstruction of photon direction.
- Selection of $\eta \rightarrow \gamma\gamma$ events.
- Careful estimates of the analysis efficiency and the detector acceptance, and their uncertainties. Careful study of other systematic uncertainties. These will be accomplished by studying simulation results as well as real data, including a full analysis of the special "active collimator" runs.

Simulation Results.

A GEANT-based Monte-Carlo simulation of the experiment was developed at UCLA. Some of the more interesting simulation results are discussed here.

During the design stages of the experiment, simulations showed that the BGO provides adequate energy resolution to distinguish between accepted $\eta \rightarrow \gamma\gamma$ events and events in which one photon hits the 8cm-thick lead collimator wall (see Figure II-2-5). It was then decided that an inactive 8cm-thick lead collimator would be sufficient for the desired experiment precision.

Also, the photon position-reconstructing algorithm uses energy sharing information from simulations. First, $\eta \rightarrow \gamma\gamma$ is simulated. An analytic function is fit to the mean true (simulated) photon position projected onto one axis, as a function of ratio of the pulse heights in adjacent BGO counters.

Then, one can use these fit results to reconstruct photon positions from the BGO pulse heights alone. Here is how one proceeds:

- For each calorimeter, the BGO counter with the largest pulse height (E_1) is chosen, and a rough position estimate is made.
- The six nearest neighbors are examined. Of these six, the counter with the largest pulse height (E_2) is chosen. If this counter passes the threshold, a position correction is applied based on the value of E_2/E_1 . This process determines one coordinate of the position.
- Of the remaining five nearest neighbors, the counter opposite the counter used in the previous step is ignored. The counter with the next largest pulse height (E_3) is chosen from the remaining four. If this counter passes the threshold, a position correction is applied based on the value of E_3/E_1 . This determines another coordinate of the position.
- Note that the two coordinate axes for which we have measurements are not orthogonal. Each coordinate estimate defines a line (i.e., $x=4$ would define a line parallel to the y-axis). The point at which the two lines intersect is our best estimate of the photon position.

The resulting position resolution for photons from *simulated* $\eta \rightarrow \gamma\gamma$ on the non-collimated detector arm is shown in Figure II-2-6.

References

- [1] Particle Data Group. Review of Particle Properties. *Phys. Rev. D* **45** (1992).
- [2] R.S. Kessler *et al.* *Phys. Rev. Lett.* **70** (1993), p.892.

Figure II-2-1: Experiment layout for the measurement of the $\text{BR}(\eta \rightarrow \gamma\gamma)$ at Saturne. The two BGO calorimeters measured the photon energies and directions. The lead collimator on the right arm defined the detector acceptance ($\sim 1.5\%$ for the largest collimator aperture). A thin veto counter on the collimated arm suppresses charged-particle background.

Experiment Conditions					
α (degrees)	d(NC) (mm)	d(C) (mm)	Comments	Estimated Number of η 's produced ($\times 10^6$)	Estimated Number of $\eta \rightarrow \gamma\gamma$ detected ($\times 10^3$)
9	640	870	Active Collimator Detector	1.6	9
9	640	870		1.1	3
9	710	870		1.3	7
9	640	870	Below p d $\rightarrow$ ^3He η Threshold		
9	540	870		1.6	9
9	640	770		1.7	10
7.5	710	960		1.9	8
9	640	960		1.6	9
9	710	960	Below Thresh. (2 energies)	1.7	10
9	640	960			
9	640	960			
6	710	960	Empty target	3.4	9
Total				15.9	74

Table II-2-1: List of experiment conditions; α is the collimator aperture half angle, and d(NC) and d(C) are the distances from the target to the front faces of the non-collimated and collimated calorimeters, respectively (see Figure I'-2-1).

Figure II-2-2: Top (bottom): The calorimeter profiles for a typical cosmic ray event ($\eta \rightarrow \gamma\gamma$ event). Each white hexagon represents one calorimeter. Within these white hexagons are some shaded regions which indicate which BGO counters "fired." The top plot shows the path of one typical nearly-vertical cosmic ray through one of the calorimeters. The bottom plot shows the response to an $\eta \rightarrow \gamma\gamma$ event, in which a photon strikes the face of each calorimeter and subsequently produces an electromagnetic shower. Such plots were available online during data taking, where they proved to be a useful diagnostic tool.

26-Aug-93 10.49

Figure II-2-3: Top: The amplitude spectrum of *one individual* BGO counter for cosmic rays acquired *between* beam spills during a $1\frac{1}{2}$ hour data run. The relative amplitude calibration is accomplished by aligning the peak of the cosmic ray amplitude spectra (of each individual BGO counter) to the same (though arbitrary) value. Data runs can be combined for improved statistics.

Bottom: The amplitude of one entire calorimeter (*i.e.*, all the amplitudes of the individual BGO counters added together, after the relative amplitude calibration) in response to $\eta \rightarrow \gamma\gamma$ (and background). The absolute energy calibration is determined by aligning the $\eta \rightarrow \gamma\gamma$ peak to its anticipated value.

26-Aug-93 11.23

Figure II-2-4: The *preliminary* invariant mass spectrum of run 83 (approximately $1\frac{1}{2}$ hours of data acquisition during the May, 1993 beam time). Notice the clean separation of $\eta \rightarrow \gamma\gamma$ from the background, which consists of mostly $\eta \rightarrow 3\pi^0 \rightarrow 6\gamma$. Later, cuts will further reduce the background. A *preliminary* analysis of run 83 yields $624 \pm 25 \pm 30$ $\eta \rightarrow \gamma\gamma$ events, $\text{BR}(\eta \rightarrow \gamma\gamma) = 0.38 \pm 0.02 \pm 0.04$.

Simulated $\eta \rightarrow \gamma\gamma$

Figure II-2-5: The collimated-arm calorimeter pulse height sum, in response to simulated $\eta \rightarrow \gamma\gamma$ events. These spectra include simulated $\eta \rightarrow \gamma\gamma$ events in which the collimator wall is hit. The photons which pass through the collimator aperture (peak on the right) are easily separable from the events in which the collimator wall is hit (peak on the left). Black shading indicates the events in which the veto counter fires.

PAW Macro: EXEC HEX_PLOTS#COLLIMATOR

09-Mar-93 12.35

Simulated $\eta \rightarrow \gamma\gamma$, Non-collimated arm (at 65 cm)

HEXz2ARMz108z65zAPER.HIS

Figure II-2-6: The *simulated* photon angles θ_x^γ and θ_y^γ are reconstructed (estimated) based only on the energy deposits in the individual counters of the calorimeter. Here, the *simulated* reconstructed photon angles θ_x^γ (top) and θ_y^γ (bottom) on the non-collimated arm are plotted as functions of the corresponding true (simulated) photon angles.

PAW MACRO: EXEC HEX_POSI_FIT#PLOT

II-3. Rare η Decays $\eta \rightarrow \mu^+\mu^-$ and $\eta \rightarrow e^+e^-$ (LNS Exp. #198).

We have completed the precision measurement of the branching ratio for $\eta \rightarrow \mu^+\mu^-$ at SATURNE (Experiment #198) using the η production reaction $pd \rightarrow {}^3\text{He } \eta$. Figure II-3-1 shows the experiment setup. The ${}^3\text{He}$ is detected and its vector momentum is measured by a spectrometer, to tag the η . Both muons were detected in range detectors, which measured the muon angles and ranges. Tests on timing, range, coplanarity, and opening angle made it possible to distinguish $\eta \rightarrow \mu^+\mu^-$ from the dominant background, $\eta \rightarrow \gamma\gamma$ and $pd \rightarrow {}^3\text{He } \pi^+\pi^-$. We define the *opening angle correlation function*, $\Delta\Theta_{\text{LR}}^{\mu^+\mu^-}$, as

$$\Delta\Theta_{\text{LR}}^{\mu^+\mu^-} = \Theta_{\text{LR}}^{\text{calculated}} - \Theta_{\text{LR}}^{\text{measured}}$$

where $\Theta_{\text{LR}}^{\text{measured}}$ is the measured opening angle subtended by the two muons, and $\Theta_{\text{LR}}^{\text{calculated}}$ is the two-muon opening angle calculated using the measured ${}^3\text{He}$ vector momentum and assuming $\eta \rightarrow \mu^+\mu^-$ kinematics. Figure II-3-2 shows the spectrum of $\Delta\Theta_{\text{LR}}^{\mu^+\mu^-}$ for both the final data sample and the Monte-Carlo simulated events which were used to determine the analysis efficiency. We obtained

$$\text{BR}(\eta \rightarrow \mu^+\mu^-) = [5.6_{-0.7}^{+0.6}(\text{stat}) \pm 0.5(\text{syst})] \times 10^{-6}. \quad [1]$$

With this result, we have been able to constrain the ratio of the $\text{BR}(\eta \rightarrow \mu^+\mu^-)$ to the $\text{BR}(\text{unitarity bound})$ to 1.3 ± 0.2 . A comparison of this result with the existing measurements of 1.5 ± 0.5 and 5.3 ± 2.1 is shown in Figure II-3-3.

Our results indicate that the decay mechanism for $\eta \rightarrow \mu^+\mu^-$ is dominated by a two-photon intermediate state, $\eta \rightarrow \gamma\gamma \rightarrow \mu^+\mu^-$. The real part of the decay amplitude, which describes the off-shell behaviour of the intermediate state, contributes less than the imaginary part as predicted by most quark and Vector Meson Dominance model calculations. There is no indication of an exotic contribution to the $\eta \rightarrow \mu^+\mu^-$ decay rate. This work has been published in Physical Review Letters [1] and a larger paper detailing the work is to be submitted to Physical Review D.

The data for this experiment were further analysed to look for the rare decay $\eta \rightarrow e^+e^-$. The present limit is based upon old data with a large background. We felt, therefore, that our data would provide an independent measurement which could verify and possibly improve this result.

The decay mechanism for $\eta \rightarrow e^+e^-$ is essentially the same as for $\eta \rightarrow \mu^+\mu^-$. The helicity factor reduces the unitarity lower bound to be $\text{BR}(\eta \rightarrow e^+e^-) > 1.75 \times 10^{-9}$, making this reaction very sensitive to exotic decay mechanisms such as the one mediated by leptoquarks. The existing limit is $\text{BR}(\eta \rightarrow e^+e^-) < 3 \times 10^{-4}$ (90% C.L.) [2].

The search for $\eta \rightarrow e^+e^-$ was done by analyzing data taken during the experiment without the pion absorbers in front of the position hodoscopes ("P" in Figure II-3-1).

This was done originally to study background due to $pd \rightarrow {}^3\text{He} \pi^+ \pi^-$. The muon stop counters ("S" in Figure II-3-1) were not used. Timing, coplanarity, pulse height, and opening angle correlation (re-defined for $\eta \rightarrow e^+ e^-$) were used to identify the $\eta \rightarrow e^+ e^-$ decay mode.

Figure II-3-4 shows a spectrum of the $\eta \rightarrow e^+ e^-$ opening angle correlation function for the final data sample. There are 9 candidates in the signal region $-2 < \Delta\Theta_{\text{LR}}^{e^+ e^-} < 2$. The expected background in the signal region, mostly multibody η decays, is 5.9 ± 1.8 . The uncertainty in the background estimate and the 22% uncertainty in the analysis efficiency and the estimated number of η 's produced were incorporated into the upper limit, using the method suggested by Cousins and Highland[3]. The final results yielded an upper limit

$$\text{BR}(\eta \rightarrow e^+ e^-) < 3 \times 10^{-4} \quad (90\% C.L.),$$

consistent with the existing results.

References:

- [1] R.S. Kessler et al., Phys. Rev. Lett. **70**, 892 (1993).
- [2] Particle Data Group. Review of Particle Properties. Phys. Rev. D **45**, S1 (1992).
- [3] R.D. Cousins and V.L. Highland, Nucl. Instr. and Meth. A **320**, 331 (1992).

Figure II-3-1. Muon detectors for $\eta \rightarrow \mu^+ \mu^-$. The basic elements of each detector are horizontal and vertical position hodoscopes (P), iron and lead moderators, horizontal and vertical trigger hodoscopes (T), and six stop-counter planes (S). The proton (p) beam is incident on the deuterium target (d), and the recoil ${}^3\text{He}$ is detected in the SPES II spectrometer (not shown).

Figure II-3-2. The angle correlation distribution (see text for definition) of the final sample. In the signal region defined as $-3^\circ < \Delta\theta_{LR}^{\mu\gamma} < 3.0^\circ$, there are $108 - 2 = 100 \pm 11$ events. The dots show the result of a Monte Carlo simulation normalized to the data; the reduced χ^2 of data/Monte Carlo is 0.9.

Figure II-3-3. The result of the present experiment compared with previous results [12-14]. The dashed line shows the unitarity (lower) bound.

Figure II-3-4. Spectrum of the $\eta \rightarrow e^+ e^-$ opening angle correlation function for the final data sample of the search for $\eta \rightarrow e^+ e^-$. There are 9 candidates in the signal region ($-2 < \Delta\Theta_{LR}^{e^+e^-} < 2$). The expected background, mostly multibody η decays, is 5.9 ± 1.8 .

II-4. The Forbidden Decay $\eta \rightarrow \mu e$ (LNS Exp. #198).

No previous search has been made for the lepton family violating decay $\eta \rightarrow \mu e$. A weak limit of $\text{BR}(\eta \rightarrow \mu e) < 8 \times 10^{-2}$ is based on the total branching ratio for η charged particle decay modes. The $\eta \rightarrow \mu e$ decay mode is complimentary to $K_L \rightarrow \mu e$ in that $\eta \rightarrow \mu e$ tests for lepton violating interactions which might couple only to $s\bar{s}$ quarks. A phenomenological limit for the branching ratio can be set for this decay via $\mu \rightarrow e$ non-coherent conversion in ^{32}S to be $\lesssim 10^{-10}$. Since no direct search of this decay mode has been made, it is useful to examine the $\eta \rightarrow \mu^+\mu^-$ data (discussed in Section II-3) in order to provide a first experimental upper limit.

The analysis for $\eta \rightarrow \mu e$ was very similar to that for the $\eta \rightarrow \mu^+\mu^-$ decay mode, except that selection was made by requiring a muon in one arm and a track in the other arm which would be consistent with an electron. Since the electron would not reach the trigger counters located behind the second absorber, these events would trigger the system via an accidental trigger only. The electron selection was made using timing and opening angle. No cuts were placed on the pulse height of the position hodoscope in the electron arm to separate electrons from pions or muons since the electrons would usually shower making their distinction via pulse height impossible. An $\eta \rightarrow \mu e$ opening angle correlation function, $\Delta\Theta_{\text{LR}}^{\mu e}$, is defined analogously to the $\eta \rightarrow \mu^+\mu^-$ and $\eta \rightarrow e^+e^-$ opening angle correlation functions of Section II-3. Figure II-4-1 shows the resulting $\Delta\Theta_{\text{LR}}^{\mu e}$ distribution along with the expected Monte Carlo signal for μe decay. The result is 3 candidates with a mean expected background $\mu_B = 4.5 \pm 1.4$.

The acceptance for this decay mode was 2.4% and the overall analysis efficiency was $\sim 10\%$. The accidental trigger efficiency was determined by two independent methods to yield an average value of $14.0 \pm 2\%$. The expected background $\mu_B = 4.5 \pm 1.4$ was estimated using the total number of events outside the signal region of $\Delta\Theta_{\text{LR}}^{\mu e}$, assuming a uniform distribution. The relative systematic uncertainty for the analysis was estimated to be 9% determined from the 2μ analysis and 14% from the accidental trigger rate or 16% combined. Correcting for the uncertainty in the value of μ_B by the same method used for the $\eta \rightarrow e^+e^-$ upper limit, our analysis places an upper limit of

$$\text{BR}(\eta \rightarrow \mu e) < 1.1 \times 10^{-5} \quad (90\% \text{C.L.}).$$

Publication of this work including the $\eta \rightarrow e^+e^-$ result is in progress.

10-Feb-83 16.57

Figure II-4-1. Top: Histogram of the opening angle correlation function $\Delta\Theta_{LR}^{\mu e}$ for the final data sample. There are 3 candidates in the signal region $-2 < \Delta\Theta_{LR}^{\mu e} < 2$; the expected background is 4.5 ± 1.4 . Bottom: Simulated $\eta \rightarrow \mu e$ which were used to determine the $\eta \rightarrow \mu e$ selection efficiency of the analysis.

II-5 The New AGS η Decay Program

II-5 A. Motivation

The η invites many tests of fundamental discrete symmetries such as C in $\eta \not\rightarrow 3\gamma$, or $\eta \not\rightarrow \pi^0\pi^0\gamma$ and $\eta \rightarrow \pi^0 e^+ e^-$, as well as CP in $\eta \not\rightarrow \pi^0\pi^0$. It is even possible to test CPT by the π^0 angular correlation with the dilepton pair in $\eta \rightarrow \pi^0\mu^+\mu^-$.

Charge conjugation, C, more appropriately called particle-antiparticle conjugation, has not been tested very well. The best limit on the validity of C invariance is $A_v < 0.1 A_c$, where A_v is the C-violating and A_c is the C-conserving strong amplitude [1]. This limit is derived from

$$BR(\eta \rightarrow \pi^0\mu^+\mu^-) < 5 \times 10^{-6}.$$

This and other tests of C are discussed in Ref. [1]. Weak interactions violate C. In the minimal Standard Model, SM, the strong and electromagnetic interactions mediated by gluons and photons respectively are C invariant, though the experimental basis for this sweeping assumption is lacking.

Tests of CP invariance are even rarer than tests of C. Outside the neutral K-meson system where CP is violated at the level $\sim 10^{-3}$, the best case is

$$BR(\eta \rightarrow \pi^+\pi^-) < 1.5 \times 10^{-3}.$$

The lack of tests of C and CP invariance is due to a critical shortage of suitable eigenstates of the C and CP operators. Neither baryons, leptons, nor charged, strange, or charmed mesons qualify. Over 90% of the known particles are excluded, only flavorless mesons and chargeless gauge bosons are eligible. This is a direct consequence of the definition of the charge conjugation operator $\hat{C}$, which changes the sign of the additive quantum numbers,

$$\hat{C}|Q, I_3, B, L_i, s, c, b; \vec{p}, \vec{J}\rangle = \eta_c^* | -Q, -I_3, -B, -L_i, -s, -c, -b; \vec{p}, \vec{J}\rangle,$$

Q is the electric charge, I_3 is the third component of isospin, B is the baryon number, L_i = lepton family number, s = strangeness, c = charm, b is beauty, $\vec{p}$ is linear momentum, $\vec{J}$ is angular momentum, and η_c^* is a nonobservable phase factor.

The best known eigenstates of C are $\gamma, \pi^0, \eta, \rho^0, \eta', \psi$, and Z . Of these, the η is most suitable because its mass allows useful decay modes and its width is sufficiently small to allow tagging. The relatively narrow width of the eta also improves the sensitivity. Consider $\Gamma(\eta) = 1.2$ keV, which is to be compared with $\Gamma(\rho^0) = 150$ MeV. This implies that the ρ^0 is a factor of 10^5 less sensitive than the η . The lifetimes of the ψ and Z are reasonably large; however, at present these particles are not produced in sufficient numbers to allow searches for rare decay modes.

In the SM, CP violations outside the neutral K and B meson systems are extremely small. If a violation of C were found in η decay, it would be a direct violation of the

SM and thereby constitute clear evidence for New Physics. The phenomenal success of the SM in electroweak tests notwithstanding, the SM is still only a model, which needs 19 input parameters. Some form of New Physics is expected. Detailed tests of the basic symmetries are a good way to search for this. Numerous ideas exist for physics beyond the SM such as supersymmetries, left-right symmetries, preons and multiple Higgs theories. These ideas have not yet been tested extensively.

At the AGS, the η can be produced readily in reactions such as $\pi^- p \rightarrow \eta n$. When the pion momentum is just above threshold, the etas and the recoil neutron emerge quasi-monochromatic and monodirectional, which greatly facilitates detection and tagging. The SLAC Crystal Ball, described in section V-1, is particularly suited for detecting the multi-photon final states from all-neutral η decays. We have submitted a proposal to the AGS to borrow the Crystal Ball and make it the centerpiece of a new AGS η facility.

References

- [1] B.M.K. Nefkens in *New Vistas in Physics with High-Energy Pion Beams*, Santa Fe, New Mexico 1992, edited by B. Gibson and J. McClelland, (World Scientific, Singapore, 1993) p. 91.

II-5 B. Testing C and CP

An impressive list of tests of the discrete symmetries C, P, CP, T, and CPT that are possible using different η decay modes is presented in Table II-5-B1. All but a few of these tests require the detection of one or more photons. Of special interest are the multi-photon decay modes.

- i) The decay $\eta \rightarrow 3\gamma$ is forbidden to occur by C-invariance. It is a third order electromagnetic transition of quarks which is suppressed by the constraints of gauge invariance and Bose symmetry imposed on the 3γ final state, and by α as compared to the allowed second order decay $\eta \rightarrow 2\gamma$ which has $BR = 0.38$. The 3γ decay mode may occur by the familiar C and P violating but CP-conserving weak interactions. The simplest effective Hamiltonian which can satisfy the just mentioned constraints has seven derivatives; this results in the branching ratio depending on the 12th power of the meson mass [1-4] and on the inverse 8th power of the effective quark mass. P. Herczeg [5] has estimated that the allowed CP-conserving decay has $BR(\eta \rightarrow 3\gamma) < 10^{-13}$ and he argues that the CP-violating contribution of the minimal Standard Model is negligibly small. Thus, a large BR of $\eta \rightarrow 3\gamma$, say at the level 10^{-7} , would be irrefutable evidence for New Physics beyond the SM.

It has been shown that in renormalizable gauge models with elementary quarks [5], the flavor-conserving nonleptonic interactions of quarks do not contain in first order a CP-violating component of class 4 mentioned at the end of Section I. This

TABLE II-5 B1 Testing C, P, CP, T, and CPT in rare η decays

Decay	Symmetry	Observable	e.m. order	Exp. Limit
$\eta \rightarrow \pi^0 \ell^+ \ell^-$ ^(a)	C	rate	$\alpha^4(\alpha^2)^b$	$< 5 \times 10^{-6}$
$\eta \rightarrow \pi^0 \ell^+ \ell^-$ ^(a)	C, CP ^(b)	charge asym.	$\alpha^4(\alpha^2)^b$	—
$\eta \rightarrow \pi^0 \mu^+ \mu^-$	T	μ^+ trans. pol.	$\alpha^4(\alpha^2)^b$	—
$\eta \rightarrow \pi^0 \mu^+ \mu^-$	T	$\mu^\pm$ pol. corr.	$\alpha^4(\alpha^2)^b$	—
$\eta \rightarrow \pi^0 \ell^+ \ell^-$ ^(a)	CPT	decay correl.	$\alpha^4(\alpha^2)^b$	—
$\eta \rightarrow 3\gamma$	C	rate	α^3	$< 5 \times 10^{-4}$
$\eta \rightarrow \mu^+ \mu^-$	P, CP	μ^+ long. pol.	α^4	—
$\eta \rightarrow \pi^+ \pi^-$	P, CP	rate	—	$< 1.5 \times 10^{-3}$
$\eta \rightarrow \pi^0 \pi^0$	P, CP	rate	—	—
$\eta \rightarrow 4\pi^0$	P, CP	rate	—	—
$\eta \rightarrow \pi^+ \pi^- \ell^+ \ell^-$ ^(a)	P, CP ^(b)	decay correl.	α^2	—
$\eta \rightarrow \pi^0 \pi^0 \gamma$	C	rate	α	—
$\eta \rightarrow \pi^+ \pi^- \gamma$	P, CP	spectral shape ^(c)	α	—
$\eta \rightarrow \pi^+ \pi^- \pi^0$	C	charge asym.	—	$< 3 \times 10^{-3}$
$\eta \rightarrow \pi^+ \pi^- \gamma$	C	charge asym.	α	$< 1 \times 10^{-2}$
$\eta \rightarrow \pi^0 \pi^0 e^+ e^-$	C	rate	$\alpha^4(\alpha^2)^b$	—

^(a) ℓ stands for μ or e

^(b) the α^4 -order is allowed while the α^2 -order is forbidden by C

^(c) bremsstrahlung component

could be a hint that the New Physics explored in $\eta \rightarrow 3\gamma$ involves composite quarks or preons.

The decay $\pi^0 \rightarrow 3\gamma$ is also forbidden by C-invariance; the experimental status is $BR < 3 \times 10^{-8}$. Because the BR depends on the 12th power of the meson mass, as stated earlier, the decay $\pi^0 \rightarrow 3\gamma$ is some seven orders of magnitude less sensitive to a possible C-violation than $\eta \rightarrow 3\gamma$.

It has been suggested to use the stringent bound on the electric dipole moment on the neutron to limit the magnitude of possible CP violations [5], but this requires a model of CP violation. An example discussed in Ref. [5] yields $BR(\eta \rightarrow 3\gamma) \leq 10^{-10}$.

The present experimental upper limit for $BR(\eta \rightarrow 3\gamma)$ is 5×10^{-4} . We plan to improve this by three to four orders of magnitude.

- ii) The decay $\eta \rightarrow \pi^0\pi^0\gamma$ is forbidden by C-invariance. It is an electromagnetic interaction of quarks of order α . The simplest configuration for the $(\pi^0 - \pi^0)$ system is a relative D-state, isospin $I=0$ and the photon multipole is a magnetic quadrupole. There is a related decay $\eta \rightarrow \pi^+\pi^-\gamma$ which is allowed; it has a BR of 5% and the dominant $(\pi^+\pi^-)$ configuration is the relative P-state, isospin $I=1$. One can relate the two decay modes after making some reasonable assumptions about pion-pion interactions [6]:

$$R_\eta = \Gamma(\eta \rightarrow \pi^0\pi^0\gamma)/\Gamma(\eta \rightarrow \pi^+\pi^-\gamma) \simeq 2 \times 10^{-4} \chi^2,$$

where $\chi = f/g$ with f the C-violating and g the C-conserving decay amplitude.

A search for the decay mode $\eta \rightarrow \pi^0\pi^0\gamma$ is a much more sensitive test of C-invariance than a test of the charge asymmetry in $\eta \rightarrow \pi^+\pi^-\gamma$ or $\eta \rightarrow \pi^+\pi^-\pi^0$ which requires a strong $\pi\pi$ interaction which does not happen at this energy.

There is no existing data on the BR for $\eta \rightarrow \pi^0\pi^0\gamma$. The level 10^{-4} is quite reasonable for the first phase of experiments at the new AGS η facility.

- iii) The decay $\eta \rightarrow \pi^0\pi^0$ is special because it is a test of CP and P invariance. The SM predictions are $\ll 10^{-10}$; any larger BR would be a sign of New Physics. There are no experimental searches reported. We can easily reach the level 10^{-3} but are then limited by the unavoidable background coming from $\pi^-p \rightarrow \pi^0\pi^0n$. This situation is analogous to the other test of CP in $\eta \rightarrow \pi^+\pi^-$ which is limited by dipion production also.

- iv) The decay mode $\eta \rightarrow \pi^0 \gamma \gamma$ is not forbidden, only suppressed. This decay mode is special because it is the input to calculations of the unitarity lower bound of the important decay $\eta \rightarrow \pi^0 \ell^+ \ell^-$ to be discussed in the next section. A measurement would give important information for low energy hadronic physics. Chiral Perturbation Theory (χ PT) provides a fine description of the strong and electromagnetic interactions of pseudoscalar mesons. Holstein [7] has recently reviewed the impressive success in relating several π , K, and η decay parameters. There is one glaring exception, namely $\eta \rightarrow \pi^0 \gamma \gamma$. χ PT predicts $\Gamma \simeq 0.42$ eV while experiment finds $\Gamma \sim 0.8 \pm 0.2$ eV or $\text{BR}(\eta \rightarrow \pi^0 \gamma \gamma) = (7.1 \pm 1.4) \times 10^{-4}$. This has prompted a stimulating debate which is ongoing. The χ PT believers are busy calculating the p^0 order terms [8]. Others are engaged in quark-box diagram calculations [9] resulting in a width of 0.7 eV. There is only one measurement of the rate and none of the spectrum. With modest effort, the Crystal Ball can measure both.

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II-5-C. The Decay Modes $\eta \rightarrow \pi^0 e^+ e^-$ and $\eta \rightarrow \pi^0 \mu^+ \mu^-$

The semi-electromagnetic decays $\eta \rightarrow \pi^0 \ell^+ \ell^-$ are especially rich in tests of the discrete symmetries, see Table II-5-B1.

A novel way for testing C is a search for the lepton charge asymmetry in the decay $\eta \rightarrow \pi^0 \ell \bar{\ell}$ where ℓ is μ or e . The underlying physics is the following. The lowest order electromagnetic interaction goes via the one photon intermediate state, Fig. II-5-C1a,

$$\eta(C = +1) \rightarrow \pi^0(C = +1) + \gamma^*(C = -1) \rightarrow \pi^0 \ell \bar{\ell}$$

which is forbidden by C conservation. The rate is proportional to α^2 . The next lowest order is based on the two photon intermediate state, Fig. II-5-C1b.

$$\eta \rightarrow \pi^0 \gamma^* \gamma^* \rightarrow \pi^0 \ell \bar{\ell}.$$

The rate is now $\sim \alpha^4$ and the decay is allowed by C and CP. The approximate branching ratio can be evaluated with the help of a unitarity-lower-bound calculation in which the imaginary part of $A(\eta \rightarrow \pi^0 \ell \bar{\ell})$ is obtained by putting the two photons of the intermediate state $\eta \rightarrow \pi^0 \gamma \gamma$ on the mass shell. Such an evaluation has been made recently by Ng and Peters [1]. The spectral distribution of the $(\pi^0 \gamma \gamma)$ intermediate state has never been measured; therefore, a modified Vector-Meson-Dominance model was used. If this is indeed applicable, one finds

$$BR(\eta \rightarrow \pi^0 \mu^+ \mu^-) > 10^{-9} \quad \text{and}$$

$$BR(\eta \rightarrow \pi^0 e^+ e^-) > 10^{-9}.$$

The last result agrees with that of Cheng [2] after an update of the input parameters. The lepton charge asymmetry parameter $\mathcal{A}$ is defined as

$$\mathcal{A} = \frac{d\Gamma(E_- > E_+) - d\Gamma(E_- < E_+)}{d\Gamma(E_- > E_+) + d\Gamma(E_- < E_+)}$$

where $d\Gamma(E_- > E_+)$ and $d\Gamma(E_- < E_+)$ denote the densities in the two halves of the Dalitz plot defined by $E_- > E_+$ and $E_- < E_+$ respectively and $E_{\pm}$ is the kinetic energy of the $\mu^{\pm}$. A nonzero value for $\mathcal{A}$ results from the interference of the C-violating one-photon amplitude $A_{\phi}(1\gamma)$ and the C-conserving two-photon amplitude $A_c(2\gamma)$. Thus,

$$\mathcal{A} \sim A_{\phi}(1\gamma) A_c(2\gamma) \sin \phi,$$

where ϕ is the interference phase which we expect to be large in this case. A nonzero value for $\mathcal{A}$ is unequivocal evidence for C violation.

The best upper limit on A_ϕ , mentioned in the Particle Data Tables, comes from $BR(\eta \rightarrow \pi^0 \mu^+ \mu^-) < 5 \times 10^{-6}$; because this decay is allowed in order α^4 , the test cannot be improved dramatically. The charge asymmetry test does not have such a limitation. To our knowledge, the $\eta \rightarrow \pi^0 \ell \bar{\ell}$ charge asymmetry test has not been proposed before as a test of C. Testing CP via the charge asymmetry in $K_L \rightarrow \pi^0 \ell \bar{\ell}$ has been suggested by Pais and Treiman [3], and details have been discussed by Sehgal [4].

Invariance under time reversal, T, which also implies CP by the CPT theorem, can be tested in the search for a transverse component of the μ^+ polarization in the decay $\eta \rightarrow \pi^0 \mu^+ \mu^-$. This component is described by the amplitude

$$A_T \sim \vec{\sigma}_{\mu^+} \cdot (\vec{p}_{\mu^+} \times \vec{p}_{\mu^-}),$$

which is odd under T. Existing spin precession techniques could be employed in the search for a possible transverse μ^+ polarization component as a clean test of time reversal invariance.

Next, we want to mention a novel test of CPT invariance based on correlations in $\eta \rightarrow \pi^0 \ell \bar{\ell}$ decay. The uncommon feat that one can test CPT using certain decay modes is based on the following: the physical meaning of the CPT operator for the decay $\eta \rightarrow \pi^0 \ell^+ \ell^-$ is to reverse all spins and interchange spins and momenta of ℓ and $\bar{\ell}$. As we have outlined in Ref. [5], CPT invariance implies that the decay spectrum of $\eta \rightarrow \pi^0 \ell \bar{\ell}$ can have only even powers of $\cos(\theta)$ where θ is the angle between the π^0 and the $\bar{\ell}$ in the dilepton c.m. frame. This is illustrated in Fig. II-5-C2.

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II-5-D. Other Physics of Rare η Decays

Besides testing the discrete symmetries of P, T, and C, the rare η decays offer a host of other interesting possibilities for testing the Standard Model, see Table II-5-D1. Consider the decay $\eta \rightarrow e^+e^-$. This is an α^+ type decay (see Fig. II-5-D1a) suppressed by the helicity factor $(m_e/m_\eta)^2$. A reliable estimate [1] is $BR(\eta \rightarrow e^+e^-) = (5 \pm 1) \times 10^{-9}$. A branching ratio much larger than this would be a significant hint for new physics such as the speculative leptoquark [2] which is a novel intermediate boson that would directly connect quarks with leptons as illustrated in Fig. II-5-D1b. The present experimental limit is $BR(\eta \rightarrow e^+e^-) < 3 \times 10^{-4}$ which could stand to be improved.

Next, we consider the decay $\eta \rightarrow \pi\ell\nu$. The simplest interaction responsible for this weak decay is the speculative second-class weak current with vector-type coupling [3]. The branching ratio for a typical allowed weak interaction would be about 10^{-9} with a possible suppression by the factor $(m_\ell/m_\eta)^2$ due to helicity conservation. Second-class weak currents are not easily renormalizable and they are not compatible with modern gauge theories [4]. Experimental tests of gauge invariance, which underlies the Standard Model, are hard to find. Thus the decay $\eta \rightarrow \pi\ell\nu$ is of fundamental interest as it provides a possible, unambiguous test of gauge invariance. Limits for the second-class weak vector current coupling for different upper limits on $\eta \rightarrow \pi e\nu$ and $\eta \rightarrow \pi\mu\nu$ have been given by Lucha et al. [5], who conclude that observation of these decays at the level 10^{-11} would point uniquely to new physics.

Lepton-family-number, LFN, conservation is a perplexing riddle for the Standard Model because the underlying symmetry is unknown. It certainly spoils some of the nice parallelisms between the 3 quark families and the 3 lepton families. The decay $\eta \rightarrow \mu e$ is an isoscalar LFN violation in which a $u\bar{u}$, $d\bar{d}$, or $s\bar{s}$ quark pair is connected to the μe lepton pair. The unique part of the η , as compared to the π^0 , is its $s\bar{s}$ component. P. Herczeg [6] has made a careful study of the sensitivity of the decay $\eta \rightarrow \mu e$ in view of existing experimental limits on LFN violation in μe conversion, $\mu \not\rightarrow e\gamma$, $K_L \not\rightarrow \mu e$, etc. He concludes that all existing information does not exclude that $BR(\eta \rightarrow \mu e)$ is possible at the level 10^{-10} or somewhat larger. Except if some special cancellation were to occur, the search for $\eta \rightarrow \mu e$ is no competition for $K_L \rightarrow \mu e$ for placing a limit on *general* LFN transitions of the kind in which the flavor of the quark does not play a role; the reason is of course that $\Gamma(\eta \rightarrow \text{all}) \simeq 10^{11} \Gamma(K_L \rightarrow \text{all})$. The importance of testing LFN conservation warrants that even the weak cases such as $\eta \rightarrow \mu e$ should be searched for in earnest. Note that unusual cases in which a special cancellation occurs exist in abundance. Take the famous GIM cancellation mechanism which was born in an effort to understand the small BR of $K_L \rightarrow \mu^+\mu^-$ in connection with the expected existence of weak neutral currents.

TABLE II-5-D1 Other interesting rare η decays

	Decay Mode	New Physics	Needed Sensitivity
1	$\eta \rightarrow e^+ e^-$	leptoquark	$BR \sim 10^{-9}$
2	$\eta \rightarrow \mu e$	lepton fam. viol.	$BR \sim 10^{-10}$
3	$\eta \rightarrow \pi \ell \nu$	2nd class current	$BR \sim 10^{-11}$
4	$\eta \rightarrow K e \nu$	ΔS weak int.	$BR \sim 10^{-13}$
5	$\eta \rightarrow \pi \pi \nu \nu$	neutral weak current	$BR \sim 10^{-10}$
6	$\eta \rightarrow \ell^+ \ell^- \gamma$	form factor	$BR \sim 10^{-4}$
7	$\eta \rightarrow \pi^0 \gamma \gamma$	chiral perturb. th.	10% in spectr.
8	$\eta \rightarrow \pi^+ \pi^- \gamma$	chiral perturb. th.	3% in shape
9	$\eta \rightarrow \pi^+ \pi^- \pi^0$	chiral perturb. th.	3% in shape

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II-5-E. η Decays with the Crystal Ball Detector

The Crystal Ball has been used for three years at SPEAR and 5 years at DORIS II. We have initiated moving this unique detector to the AGS for use in the C-8 line. The properties of the Crystal Ball are well known and they have been detailed in the literature. We are dealing here with an existing detector and it is not necessary to establish its credentials in special development runs. However, we will need to reinstate and test all electronics, check out a new data readout system, and reestablish and verify the energy calibration procedures of all 672 NaI crystals. We must bring the 4 tracker chambers into operation and measure their efficiency. To optimize the operation of the Crystal Ball, it will be necessary to install new endcaps.

A substantial effort will go into bringing a properly tuned pion beam onto the H_2 target inside the ball, and to investigate and then reduce the backgrounds coming from the AGS production targets and from the beam, its collimator, and beam stop. The individual pions are analyzed in momentum and direction by the LESB II spectrometer with $\sigma(\Delta p) = 0.1\%$ and $\sigma(x) \simeq 0.1$ cm at the target. The pion direction resolution is $\sigma(\theta) \simeq 1$ mrad.

The third effort is the installation and tuning of the neutron tagging counters, beam monitors, and beam anti-counter. Detailed studies are needed of the tagging efficiency under various conditions.

Using a 1 cm liq. H_2 target which corresponds to 4×10^{22} protons/cm² and a π^- beam of $1 \times 10^6 \pi^-/\text{sec}$ or $3.6 \times 10^6 \pi^-/\text{pulse}$, we obtain at $p_\pi = 710$ MeV/c the event rates given in Table II-5-E1.

TABLE II-5-E1 Event Rates for $1 \times 10^6 \pi^-/\text{sec}$
and 1 cm LH_2 target

Total interactions in tgt ($\sigma_t = 45\text{mb}$)	1800 int/sec
Total neutral signal ($\sigma_n = 12\text{mb}$)	480 int/sec
Total η 's produced ($\sigma_\eta = 1.5\text{mb}$)	60 η/sec ($5 \times 10^6 \eta/\text{day}$)
η tagging efficiency = 20%	12 $\bar{\eta}/\text{sec}$ ($1 \times 10^6 \bar{\eta}/\text{day}$)

During the test and tune-up phase of the planned experiment, which we expect to require 750 hours total, we plan to run some time with an open trigger, where open means a neutron trigger only and no requirements on the crystal ball or tracker. This means that we look at all eta decays in a totally unbiased way. The maximum data acquisition rate of the existing electronics is 20 per pulse or 5 Hz; we expect to improve that to 500 Hz. A raw tag-to-background ratio of $\frac{1}{4}$ would imply looking at $5 \times 10^5 \eta/\text{day}$. Table II-5-E2 shows the kind of results that are obtained for various eta decays per $10^6 \eta$ which is typically 2 days of running.

We are performing Monte Carlo studies of possible background for the 3γ decay mode, e.g., due to the $3\pi^0 \eta$ decay. Because the Crystal Ball cannot resolve two photons which are within $2^\circ - 3^\circ$ of each other, a small number of these $3\pi^0$ decays can appear as false 3γ events. In a study, we generated 10^7 events for $\pi^- + p \rightarrow n + \eta \rightarrow n + 3\pi^0 \rightarrow n + 6\gamma$ for our nominal beam momentum of 710 MeV/c. A uniform phase space distribution was used. We then searched for events in which the six photons overlapped in pairs with the paired photons having an angle smaller than 5° . The dominant type of event had three of the six photons with a relatively small angle between their trajectories. These would be detected as 4γ events and therefore could be eliminated. There were only 2 events which satisfied the requirements of a 3γ event. Since the branching ratio of $3\pi^0$ is $\sim 32\%$, this translates to a sensitivity of 6×10^{-8} . Various improvements are being investigated. Other important Monte Carlo studies concern the background due to $\eta \rightarrow \pi^0 \gamma \gamma$.

The non-eta background, due, e.g., to π^- interactions in the target and target wall, is measured in detail by collecting an adequate amount of data with the beam momentum just below η production threshold. Monitoring of the eta production rate is accomplished by a separate event stream of scaled $\eta \rightarrow 2\gamma$ events.

A beam of $1 \times 10^6 \pi^-/\text{sec}$ yields $2 \times 10^5 \eta$ per hour or $10^8 \eta$ in a 500 hour data run. An overall detection efficiency of 70% for clean $\eta \rightarrow 3\gamma$ events and 20% tagging efficiency yields a sensitivity of 8×10^{-8} for the branching ratio. If autotagging is proven to be sufficient, the sensitivity will be a factor of 5 better or about 2×10^{-8} . We estimate needing 250 hours of background measurements mainly below η threshold. The total data taking time is therefore 750 hours.

Data analysis will be based on several criteria: (a) the invariant mass of the three gammas must be 547 MeV within a narrow tolerance; (b) at $p_\pi = 710$ MeV/c, the kinetic energy of the η must be (74 ± 37) MeV; (c) the momentum vector of the η as deduced from the 3 gammas must obey the strict rules of the two-body production process (e.g., if $p_\eta = 224$ MeV/c, then θ_η must be 10.9°); (d) the invariant mass of any pair of gammas is not that of the π^0 ; (e) finally, for the 20% sample that is accompanied by a recoil neutron tag, the eta momentum is completely determined by the recoil neutron kinematics.

The time table is as follows:

- (a) Move the Crystal Ball and all its accessories to BNL by the end of 1993. Refurbish the elevator used to separate the two halves of the Ball for access to its interior. Test the PM tubes and electronics.
- (b) Install the Crystal Ball in the late spring or early summer of 1994 after completion of the current experiment in line C8.
- (c) Start operation in 1995.

TABLE II-5-E2 Results of investigating $10^0 \eta$ decays
(2 days running with an open trigger)

η Decay Mode	Measured BR	Expect. Yield or BR Lim.
2γ	39%	calibration
$3\pi^0$	$(31.9 \pm 0.4)\%$	calibration
$\pi^0\gamma\gamma$	$(7 \pm 1) \times 10^{-4}$	560 events [†]
$\pi^+\pi^-\pi^0$	24%	—
$\pi^+\pi^-\gamma$	4.9%	—
$e^+e^-\gamma$	$(5.0 \pm 1.2) \times 10^{-3}$	4000 events [†]
$\mu^+\mu^-\gamma$	$(3.1 \pm 0.4) \times 10^{-4}$	240 events [†]
e^+e^-	$< 3 \times 10^{-4}$	?
$\mu^+\mu^-$	$(5.6 \pm 0.7) \times 10^{-6}$	—
3γ	$< 5 \times 10^{-4}$	$< 2 \times 10^{-6} *$
$\pi^0\pi^0$	—	$\sim 10^{-3}$
$\pi^0\pi^0\gamma$	—	$\sim 10^{-4}$
$\pi^0e^+e^-$	$< 4 \times 10^{-5}$	$\sim 2 \times 10^{-6} *$
$\pi^0\mu^+\mu^-$	$< 5 \times 10^{-6}$	$\sim 2 \times 10^{-6} *$
μe	$< 1.1 \times 10^{-5}$	$\sim 2 \times 10^{-6} *$

[†] Assuming 80% efficiency; * Assuming 50% efficiency

The main objective of this run is the investigation of $\eta \rightarrow 3\gamma$. For this we will use a Crystal Ball trigger of exactly 3 gammas, each gamma having an energy larger than 50 MeV. Also, the total energy in the ball must exceed 550 MeV. No tagging is required in the hardware trigger. The neutron counters will be latched instead. Of course, there is a veto on all charged final states. This trigger eliminates all major η decay modes.

Fig. II-5-C1 Feynman diagrams for $\eta \rightarrow \pi^0 \ell \bar{\ell}$

- (a) one photon intermediate state, forbidden by C-invariance;
- (b) allowed, two photon intermediate state.

Fig. II-5-C2 Pictorial representation of the effects of the CPT operator on the spin and momentum in $\eta \rightarrow \pi^0 \mu^+ \mu^-$.

Fig. II-5-D1 Feynman diagram for $\eta \rightarrow e^+e^-$
 (a) via the intermediate state of two photons;
 (b) via leptoquark.

PROGRAM III: *Baryon Spectroscopy*

III-1 Introduction

Strong-interaction physics at intermediate energies — the region where the energy is not asymptotically high and therefore QCD is not a practical model — has a great need for detailed and complete baryon spectroscopy; this has been emphasized many times [1]. Examples of the important open questions are the quantitative description of confinement and the role of gluons in low-energy interactions. An intriguing mystery in baryon spectroscopy is the phenomenon of clusters of resonances, which are groups of states that have nearly the same mass but a different spin. Various models of baryon interactions, such as (a) string, flux-tube and two-body relativistic and non-relativistic potential models, (b) bags of various types, (c) collective and algebraic models, (d) Skyrmions and non-topological partners, and (e) QCD sum rules, are all in need of more detailed information on the masses, widths, and decay rates of the resonances. The baryon program at CEBAF certainly needs better resonance data and so does some of the phenomenology of heavy ion physics planned for RHIC.

A serious flaw in the otherwise highly successful Simple Quark Model concerns the existence of exotic states such as $(4q)\bar{q}$. Various considerations imply that exotic states must exist; many have moderate mass, $1.5\text{--}2\text{ GeV}/c^2$, but there is no convincing experimental evidence for their occurrence despite substantial efforts. The excuse is that the exotic states decay preferentially to channels that are difficult to measure. Many of the proposed exotic states can decay by η emission such as $\Delta^* \rightarrow \Delta^{++} + \eta$.

One of the advantages of studying baryon spectroscopy via the η channel is the isospin selectivity due to the fact that the η has $I = 0$. The reaction $\pi^- p \rightarrow \eta n$ selects the $I = \frac{1}{2}$ resonances. There is no need for CEX-data, $\pi^- p \rightarrow \pi^0 n$, to unravel the isospin structure of the $\pi^- p$ scattering amplitudes. The isospin selectivity of the η channel can also be used for hyperon spectroscopy. The reaction $K^- p \rightarrow \eta \Lambda$ filters out the $I = 0$ states and $K^- p \rightarrow \eta \Sigma^0$ the $I = 1$ states, whereas $K^- p \rightarrow \pi \Sigma$ is a mixture of $I = 0$ and 1.

The spectroscopy of the πN resonances has been a great but unfinished success story for the quark model. In the non-strange sector of the simplest $SU(3)$ flavor classification, there are the N^* states (isospin $I = \frac{1}{2}$), which are part of an octet, and the Δ states ($I = \frac{3}{2}$), part of a decuplet.

The status of the various baryonic resonances is summarized in the Particle Data Tables (PDT) with the aid of the star system. Reliable resonances are given four or three stars while weak candidates receive only one or two stars. About half of the known resonances fall in the latter category which underscores the need for improved data. All N^* and Δ resonance properties are obtained from πN partial wave analyses (PWA) of which there are three. There is the VPI (Virginia Polytechnic Institute), the C-L (Carnegie-Mellon-Lawrence Berkeley Laboratory), and K-H (Karlsruhe-Helsinki)

analysis. The phase ambiguities inherent to all PWA's are solved by C-L and K-H with the aid of dispersion relations.

A frequently quoted paper with predictions for baryon-decay amplitudes is the work by Koniuk and Isgur [2]. They have calculated the pseudoscalar and photon couplings based on the Isgur-Karl nonrelativistic quark model [3] that incorporates many features suggested by quantum chromodynamics.

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III-2. Eta Production by Photons at ELSA.

Baryon spectroscopy has been studied since the early 1950s using π production and scattering. η production may be similarly used. η scattering is not experimentally feasible, due to the short lifetime ($5.5 \times 10^{-19} s$). The η , having a different mass and quark structure than the π , is an independent probe of resonance structure. This program looked at η photoproduction on the proton, $\gamma p \rightarrow \eta p$. The photon energy threshold for $\gamma p \rightarrow \eta p$ is $707.2 MeV$.

There are three nearby resonances that can contribute to η photoproduction: $P_{11}(1440)$, $D_{13}(1520)$, and $S_{11}(1535)$. We therefore expect resonance production to be important[1], in contrast to production of the π ; the nearest resonance to the $\pi^0 p$ threshold is the $P_{33}(1232)$, $150 MeV$ away.

For a photon energy of $730 MeV$, the c.m. momentum of the outgoing η , $\vec{p}_\eta$, is $100 MeV$, or $\lambda \simeq 2 fm$. This wavelength is larger than the typical strong interaction length of $\simeq 1 fm$. Thus, we expect the scattering to be predominantly S-wave up to this energy, with a flat angular distribution.

At threshold, both of the outgoing particles are at rest in the center-of-mass frame. This precludes production of the D_{13} ; since it has $J = 3/2$, it cannot couple to the $|\eta N\rangle$ state with the orbital angular momentum $\ell = 0$. Production of the P_{11} is still possible, but the P_{11} lies well below the threshold for $\gamma p \rightarrow \eta p$; only the tail of this resonance would contribute. Since the S_{11} mass is near the threshold for η production, we expect $\gamma p \rightarrow \eta p$ in that energy range to be dominated by the S_{11} .

Currently, there is considerable uncertainty about the mass of the S_{11} . The Particle Data Group lists it as $1535 MeV$. Recent studies by Arima *et al.* [2] and Clajus and Nefkens [3] indicate that the mass of the S_{11} may actually be around $1500 MeV$. The effect of the S_{11} mass is seen in the matrix element for $\gamma p \rightarrow \eta p$; if the mass is near the threshold for $\gamma p \rightarrow \eta p$, the matrix element will be roughly constant (note that the S_{11} is a broad resonance, with a width of approximately $150 MeV$). If the mass is well above threshold, the matrix element rises with the incident photon energy, as the S_{11} is produced more copiously. If the mass is well below threshold, the matrix element decreases as the incident photon energy increases, as the production of S_{11} falls off. Studies of η production near threshold are therefore of great interest in determining the mass and width of the S_{11} .

There are only eight data points below $E_\gamma = 800 MeV$, shown in Fig. III-2-1. The paucity of data, combined with the disagreement at $E_\gamma \simeq 730 MeV$, stimulated the measurement of this process.

A frequently used method for measuring the process $\gamma p \rightarrow \eta p$ is to detect the decay products of the eta. The mass of the decayed particle may then be determined by reconstruction. This is easiest for two-body decays, and most η photoproduction experiments involve detection of the photons from the decay $\eta \rightarrow \gamma\gamma$. The disadvantages of this

method are that it requires good knowledge of the branching ratio for $\eta \rightarrow \gamma\gamma$, and that most detectors have limited acceptance for multibody decay systems.

One can minimize both of these problems by detecting the recoil proton, and inferring η production using two-body kinematics. For photon energies near threshold, the recoil protons have very little kinetic energy in the c.m. frame. Thus, they emerge in a small cone centered about the beam axis. As the energy decreases, the opening angle of this cone decreases until, at threshold, all the recoil protons emerge at 0° . Thus, with a relatively small detector, we can obtain results for the entire range of c.m. solid angles. Kinematics limits the usefulness of this method to the energy region near threshold. To see this, note that the number of events detected depends on both the cross section and the acceptance of the detector.

A disadvantage of this method, called the Jacobian Spike technique, is that by detecting only the proton, one cannot distinguish background events that mimic the kinematics of η photoproduction. This can occur in the process $\gamma p \rightarrow 2\pi p$, where the two pions have an invariant mass equal to that of the η . A proton from such a process constitutes a background that cannot be removed with cuts on the data. Such events must be subtracted after all the other cuts have been made.

The experiment was performed at the Physikalisches Institut der Universität Bonn, using the ELSA (ELectron Stretcher Accelerator) facility. At this accelerator complex, electrons are accelerated to 50 MeV by a linac and then injected into the Bonn 2.5 GeV Synchrotron. This synchrotron accelerates the electrons to 2.5 GeV and injects them into ELSA for further acceleration to 3.5 GeV with expansion of the duty cycle to approximately 35%. For this experiment the 2.5 GeV synchrotron is tuned to 1.0 GeV, and ELSA does no acceleration. Some of the electrons are extracted into the PHOENICS (PHOTon Experiments on Nuclei In Counter Setups) area by deflecting them with a tungsten wire. A septum magnet guides them into the experimental area.

The PHOENICS tagging system is used to determine the photon energies and rates in this experiment. The main components of the tagging system are the radiator, bending magnet, and tagging hodoscope. Electrons extracted from ELSA are directed onto the radiator, which is a gold foil of thickness 10^{-3} radiation lengths, to produce photons by Bremsstrahlung. The energy dependence of the photon rate in the region of interest is $1/E_\gamma$, where E_γ is the photon energy. The electrons are momentum analyzed by the bending magnet. At the focal plane of the bending magnet is a two-layer hodoscope to detect the electrons associated with Bremsstrahlung.

The detector setup specific to the measurement of $\gamma p \rightarrow \eta p$ is shown in Fig. III-2-2. This experiment used a cylindrical liquid hydrogen target which was designed and built at Bonn by the Polarized Targets (PT) group. The axis of the target was along the photon beam. The target was 2 cm in diameter, and 8.0 ± 0.1 cm long.

The recoil protons were first detected by a double-ended scintillation counter, designated the start counter (SC). It consisted of a sheet of plastic scintillator, $12 \times 20 \times 0.5$ cm³,

viewed by phototubes at both ends (labeled $SC1 - SC2$). Adiabatic light guides were glued to the scintillator using optical cement. The interface between the light guides and the phototubes was air. The reduced light collection due to reflection at the interface was offset by ease of construction and flexibility.

Timing and pulse height information were recorded for both tubes. The two timing signals went into a mean timer to produce the start signal used for all TDCs. By using a mean timer, we reduced the dependence of the timing on the impact position of the proton on the SC.

AMADEUS (A Matrix DEtector Using a Scintillator) is a scintillation detector designed to give position and timing information simultaneously with good resolution. It was built by G. Anton *et al.* of Bonn, and is described in detail in Refs. [8] and [9]. The basic components are a block of plastic scintillator, $25 \times 40 \times 8 \text{ cm}^3$, a plexiglass light guide, and 12 phototubes (labeled $AM1 - AM12$) arranged in a rectangular array. A schematic diagram of AMADEUS is given in Fig. III-2-3.

The underlying idea of AMADEUS is that the distribution of pulse heights among the PMTs allows a precise determination of the place of incidence on the face of the detector, which in turn determines the lab angle of the outgoing particle. The sum of the pulse heights in all of the phototubes is a measure of the energy deposited in the scintillator, which can be used with the TOF information for particle identification. Knowledge of the lab angle, TOF, and particle ID allows the determination of the c.m. angle, which can then be used to calculate the missing mass.

The analysis consisted of time walk and TDC alignment corrections, timing and pulse height calibrations, and calibrating the photon energy corresponding to each EC. Empty target background was found to be negligible. The $\gamma p \rightarrow \eta p$ events were identified by the momentum dispersion of the proton, defined by the equation

$$\frac{\delta p}{p} = \frac{p_p - p_p^0}{p_p^0}, \quad (1)$$

where p_p is the recoil proton momentum and p_p^0 is the recoil proton momentum at threshold for $\gamma p \rightarrow \eta p$. The background subtraction was performed using the momentum dispersion spectra below threshold.

Fig. III-2-1 shows the results for three of our six data sets below 720 MeV, with the previous data shown for comparison. The "UCLA Model" shown in the figure is a fit to our points assuming an S-wave dependence with a constant matrix element for the cross section. This implicitly assumes that the $S_{11}(1535)$ mass is relatively near the threshold, and that it is broad enough so that we see no effect; if it were well above threshold, we would see the cross section rising much faster than a simple S-wave, as described earlier. We see a good agreement with S-wave dependence.

Assuming the energy dependence of the cross section follows the UCLA model, our results disagree with Dytman *et al.* at $\langle E_\gamma \rangle_{\gamma p \rightarrow \eta p} = 725 \text{ MeV}$, but the agreement is much

better at 750 MeV . Of the data sets shown in the figure, our model agrees best with that of Delcourt *et al.* Our results suggest a slightly faster rise in the cross section than predicted by either Benmerrouche *et al.* or Tiator *et al.*, but the difference is small.

We stated that η photoproduction should be affected by resonance production much more than π^0 photoproduction, since the $P_{33}(1232)$ lies over 150 MeV above the π^0 photoproduction threshold. The effect of the S_{11} on η photoproduction is clear: 5 MeV above threshold, the cross section for $\gamma p \rightarrow \eta p$ is an order of magnitude larger than that for $\gamma p \rightarrow \pi^0 p$ at a corresponding energy. The proximity of the S_{11} to the $\gamma p \rightarrow \eta p$ threshold enhances the cross section greatly.

We have shown that the Jacobian Spike method is a viable means of measuring η production near threshold. It is based solely on the detection of the recoil proton, and exploits the high acceptance and signal/background ratio available in the forward direction to compensate for the reduced cross section that prevents precision measurements in experiments that detect the decay products of the η . It is not as useful at photon energies far above threshold, due to the limited acceptance and lower signal/background ratio.

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Figure III-2-1: Our results for $\sigma_{\gamma p \rightarrow \eta p}$ are shown in solid black circles. Prepost *et al.* data are from Ref. [4]; Delcourt *et al.*, Ref. [5]; Erbe *et al.*, Ref. [6]; Dytman *et al.* are preliminary results as reported in Ref. [1]. The "UCLA Model" is the result of a fit of an S-wave production cross section to our points; the model of Benmerrouche *et al.* is from Ref. [1]; Tiator *et al.*, Ref. [7].

Figure III-2-2: The setup for the $\gamma p \rightarrow \eta p$ measurement.

Figure III-2-3: The AMADEUS Detector. a) Front view. b) Side view.

III-3 Eta Production by Photons at CEBAF

The existing meager eta photoproduction data on hydrogen is shown in Fig. III-3-1. It resembles the gross features of eta production by π^- on hydrogen shown in Fig. III-3-2. The tagged bremsstrahlung photon beam now under construction at CEBAF in Hall B in conjunction with the CEBAF Large Acceptance Spectrometer, provides a suitable device for detailed measurements of η photoproduction. Our collaborative proposal, CEBAF Exp. #91-008 by the CLAS collaboration, has been approved for 26 days of running concurrently with PR-89-004. Simultaneously with the η measurement, we plan to measure η' production for which there is only selective data available.

Fig. III-3-1 The world data for $\gamma p \rightarrow \eta p$ except the threshold data of our Program III-2.

Fig. III-3-2 The available "star" data on $\pi^- p \rightarrow \eta n$.

III-4 Eta Production by Pions (AGS and PNPI Exps.)

The study of eta production in the reactions $\pi^- p \rightarrow \eta n$ and $\pi d \rightarrow NN\eta$ is extremely interesting for several reasons, some of which are discussed in more detail elsewhere in this report. Both reactions are intended to be used for tagged η production in conjunction with the eta-decay studies planned at the AGS using the SLAC Crystal Ball. The reaction $\pi^- p \rightarrow \eta n$, being a two-body process, permits tighter kinematic restrictions, to the point of allowing autotagging (by reconstructing the η invariant mass from the detected decay products). Also, for the study of all-neutral eta-decay modes, this production process preserves the neutrality of the final state as a simple but powerful trigger condition. On the other hand, $\pi^+ d \rightarrow pp\eta$ offers the advantage of a higher tagging efficiency than $\pi^- p \rightarrow \eta n$, which is hampered by a neutron detection efficiency that cannot reasonably be expected to exceed 40%.

Apart from being well suited for tagged eta production, either process deserves considerable attention in its own right. By investigating eta production in $\pi^- p \rightarrow \eta n$, we gain access to the spectrum of isospin $I = \frac{1}{2}$ nucleon resonances without the admixture of $I = \frac{3}{2}$ states that complicate pion-nucleon elastic and charge-exchange scattering. The status of experimental data for pion-induced eta production is rather poor [1]. Near threshold, there are several measurements, but at most one of them appears precise enough to reliably map out the rapid variation of the cross section in this region. The results from this measurement [2], however, do not extend high enough in energy to cover the first peak in the excitation function. This peak is caused by a combination of effects due to the eta production threshold and the $S_{11}(1535)$ resonance [3]; disentangling these two effects requires even more precise data. The situation is certainly not improved by the fact that the only set of polarization data available for the reaction $\pi^- p \rightarrow \eta n$ [4] cannot be considered reliable, since the cross sections measured in the same experiment [5] turned out to be seriously flawed [1]. At higher energies, the amount of data is just sufficient to indicate some interesting structures that merit closer attention.

Eta production in πd scattering is an excellent tool for the investigation of charge symmetry (CS), especially in view of the role that $\pi^0 - \eta$ mixing is expected to play in CS breaking. In addition, the process can provide information on the model that relates the eta production process on the deuteron to the underlying single-nucleon process, e.g. impulse approximation. Using such a model, we can hope to gain information about the reaction $\pi^+ n \rightarrow \eta p$, which is the charge-symmetric counterpart of $\pi^- p \rightarrow \eta n$.

We are currently involved in two experiments that deal with pion-induced eta production. The main emphasis of AGS experiment 890 is on the investigation of CS in $\pi d \rightarrow NN\eta$. In Section I-2, the setup for measuring eta production in $\pi^\pm d$ scattering is discussed in detail. It uses a two-arm photon spectrometer to detect the decay products from $\eta \rightarrow 2\gamma$. A sample spectrum of the two-photon invariant mass measured in the process $\pi^+ d \rightarrow 2\gamma + X$ is shown in Fig. I-2-7. Suitably normalized data from background runs using Carbon and empty targets was subtracted from the spectrum measured with a

CD₂ target in order to obtain this plot. Preliminary results indicate that the eta production cross section at $p_\pi = 720$ MeV/c is smaller than would be expected from an impulse approximation using $\pi^- p \rightarrow \eta n$ data.

Some of the beam time for experiment 890 is and will be devoted to studying $\pi^- p \rightarrow \eta n$. The purpose of this is twofold. First, in preparation for our planned experiments with the Crystal Ball, we want to demonstrate the feasibility of eta tagging by detection of the recoil neutrons from the production process. Secondly, in view of the dire need for better data for baryon spectroscopy we intend to make use of the good momentum resolution, obtained by individually tracking each incident pion, to improve the cross section data near threshold.

Our experiment setup enabled us to identify eta production by detecting either the recoil neutron (i.e. using the Jacobian Spike method described in Sec. III-2) or the photons from the decay $\eta \rightarrow 2\gamma$. To achieve this, the setup consisted of the LANL η spectrometer and two groups of three neutron counters each. The beam flux was monitored by seven pairs of scintillation detectors measuring elastic pion scattering. Even though most of these monitors were set up for πd scattering, the kinematics of πp scattering is close enough so they could be used with our CH₂ target. In addition, signals from the beam-defining ST counter were fed into a scaler to determine the beam rate. The setup is described in more detail in Section I-2.

When using the η spectrometer, we calculated the two-photon invariant mass $m_{\gamma\gamma}$ from the measured photon energies and opening angle. A spectrum of $m_{\gamma\gamma}$ is shown in Fig. I-2-5. For subtracting the carbon background caused by the use of a CH₂ target, the most reliable method turned out to be the comparison with π^+ scattering on the same target. While the scattering off carbon is the same as for π^- due to CS, there can be no eta production in $\pi^+ p$ scattering at energies near the threshold for $\pi^- p \rightarrow \eta n$. The subtraction is also shown in Fig. I-2-5. The resulting spectrum shows a clean peak centered at the eta mass. At the present stage of the analysis it is too early to make any quantitative statement about the cross section.

Fig. III-4-1 shows the effect of the eta production threshold. The three $m_{\gamma\gamma}$ spectra shown here are from π^- scattering on CH₂ for three different pion momenta below and above the threshold for $\pi^- p \rightarrow \eta n$; no carbon background is subtracted. In all three spectra there is an eta signal, which can be expected, since the threshold for eta production on carbon is well below the momenta shown here. At $p_\pi = 688$ MeV/c, however, the peak is much more pronounced, indicating the onset of eta production on hydrogen.

In the case of recoil neutron detection, the eta was identified via the neutron momentum inferred from its time of flight. Threshold kinematics limits the neutron momenta to two narrowly defined ranges corresponding to forward and backward scattering in the c.m. system. The analysis of the data obtained with this method is still in its earliest stages.

The same method, detection of the recoil neutrons, is used in our second experiment

investigating the reaction $\pi^- p \rightarrow \eta n$ near threshold. This experiment is performed at the St. Petersburg Nuclear Physics Institute (PNPI) in Gatchina, Russia, in collaboration with physicists from PNPI and Abilene Christian University (ACU). The setup is shown in Fig. III-4-2. Pions impinge on a liquid hydrogen target (T) after passing through two beam-defining scintillation counters (S1 and S2) and a Čerenkov detector (C) that serves to suppress electron contamination of the beam. A scintillator hodoscope (not shown) is used to determine the individual pion momenta to within 5 MeV/c. The target is surrounded by charged-particle veto counters (V1 to V5). Recoil neutrons from eta production are detected in five sets of three neutron counters (N1 to N5). These detectors are of the same type as those used at the AGS. To shield the neutron counters from the beam, the pions are deflected by a large-gap magnet (M). They are then detected by two beam veto counters (S3 and S4) used to suppress false triggers caused by accidental coincidences between a neutron counter pulse and signals in the beam-defining counters.

Data taking for this experiment took place in the summer of 1991, the summer of 1992 (without participation by a physicist from UCLA) and in December, 1992. Several shorter runs, aimed mainly at answering questions concerning experimental details, were performed between the main runs by our Russian collaborators alone. The data are currently being analyzed at PNPI and ACU. A sample neutron counter TDC spectrum is shown in Fig. III-4-3. The two peaks due to eta production are clearly distinguished from the exponentially decreasing background due to multi-pion production. The shape of this background was determined from data taken below threshold. One of the next steps towards quantitative results will involve modeling the background based on existing two-pion production data.

In the near future, the cross section measurements in Gatchina, due to rate limitations, will not be able to compete with our baryon spectroscopy program planned at the AGS (see Sec. III-7). There are, however, fields that cannot be covered easily by this new program. For example, polarization measurements require the use of a polarized proton target, whose installation in the SLAC Crystal Ball would be extremely difficult to realize. On the other hand, such a target would be available in Gatchina. In view of the complete lack of polarization data discussed above, four of the six neutron counters that currently at the PNPI will therefore be left in Gatchina for an additional time period; the remaining two are to be shipped to Brookhaven in fall of 1993 to be used for further investigations of eta tagging in spring of 1994.

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Figure III-4-1: Two-photon invariant mass spectra for three different pion momenta near the threshold for $\pi^-p \rightarrow \eta n$. The onset of eta production on hydrogen is marked by a significantly more prominent eta peak.

Figure III-4-2: Schematic layout of the setup used in the experiment at PNPI

Figure III-4-3: Sample TDC spectrum of a neutron counter. The solid curve shows a fit by a set of Gaussians superimposed on an exponential background, mostly from two-pion production, whose shape was determined from data taken below the eta threshold.

III-5 Eta Production by Protons on Deuterium near Threshold

The differential and total cross sections for the reaction $pd \rightarrow \eta \ ^3\text{He}$ near threshold have been measured at Saturne by the same international collaboration that had measured the branching ratio for $\eta \rightarrow \mu^+ \mu^-$, see Section II-3. It was accomplished during test runs for that BR measurement to optimize the running parameters of the Saclay eta factory.

Eta production is investigated by measuring the recoil ^3He using the SPES II magnetic spectrometer. This is a specially constructed two dipole setup that allows 0° measurements of charged particles that have a different magnetic rigidity than the incident proton beam. It uses three wire chambers, a hodoscope and counters for dE/dx and TOF determinations. Near threshold, the recoil ^3He emerges in a very small forward cone. Up to 11 MeV above threshold, the entire angular distribution can be measured at once with the acceptance of SPES II.

The total cross section rises very rapidly up to 1.5 MeV above threshold, after which it is nearly constant, see Fig. III-5-1. This is very different from π^0 production near threshold, see Section IV-2, where $\sigma_t \propto \bar{p}_\eta \propto \sqrt{\Delta T_p}$; ΔT_p is the energy of the incident proton above η production threshold. This is the expected cross section dependence for S-wave production. The angular distribution at all 6 incident energies is isotropic, see Fig. III-5-2, which is especially unexpected when compared to π^0 production, because the transition form factor yields an angular distribution that is proportional to $a + b \cos \theta$. This has led to speculations about the possible existence of an $\eta \ ^3\text{He}$ quasi-bound state. This subject will be discussed further in Section IV-1.

Fig. III-5-1 $\sigma_t(pd \rightarrow \eta {}^3\text{He})$ as measured in LNS Exp. #198.

Fig. III-5-2 $d\sigma/d\Omega(pd \rightarrow \eta {}^3\text{He})$ at 11 MeV above threshold, measured in LNS Exp. #198.

III-6 Eta Production by Protons on Protons

The reaction $pp \rightarrow pp\eta$ near threshold has been measured at Saclay by a Strasbourg-Orsay-LNS-Beer Sheva-UCLA collaboration, LNS Exp. #174. The experiment technique is based on measuring both final-state protons and using the kinematics of the reaction to select the η production events. The experiment was performed at Saturne II with the SPES III spectrometer in the 0° position. SPES III is a large momentum bite (600–1400 MeV/c), large acceptance (10^{-2} sr) magnetic spectrometer. It is equipped with 3 large drift chambers and four scintillator hodoscopes for dE/dx and TOF measurements. The event extraction is based on the missing mass technique; the quality is illustrated in Figs. III-6-1 and III-6-2. The η production threshold is $T_p = 1254.6$ MeV. The total cross section was measured at $T_p = 1260, 1265,$ and 1300 MeV to be $90 \pm 15, 790 \pm 220,$ and 3400 ± 700 nb respectively. None of the existing perturbative model calculations reproduces the energy dependence which deviates greatly from phase space, see Fig. III-6-3. The likely cause is cross section enhancement near threshold due to a large ηp scattering length.

Fig. III-6-1 Scatter diagram of two-proton events in $pp \rightarrow pp\pi$ measured in LNS Exp. #174.

Fig. III-6-2 Yield versus missing mass for two-proton events in $pp \rightarrow pp\eta$ obtained in LNS Exp. #174.

Fig. III-6-3 $\sigma_t(pp \rightarrow pp\eta)$ measured in Exp. #174. The dashed curves are theoretical calculations, the solid line is the S-wave production arbitrarily normalized.

III-7 New Investigations of N^* and Hyperon Resonances with the Crystal Ball (Letter of Intent to AGS)

III-7-A. Motivation

A new approach to baryon spectroscopy involving multi-photon final states becomes possible by using a 4π solid angle electromagnetic calorimeter and spectrometer instead of the traditional meson spectrometer. The latter typically has an acceptance of 1%; in order to measure a complete angular distribution, the configuration of the spectrometer arms needs to be changed repeatedly, often a time consuming task.

The SLAC Crystal Ball is exceptionally well suited for the determination of the η decay branch of various resonances. This detector consists of a hollow ball, which is made of 672 NaI crystals with individual readout, and a charged particle tracker which is inside the ball and surrounds the target, see Section V-1. The two largest η decay modes are to multi-photon final states: $\eta \rightarrow 2\gamma$ with BR = 38% and $\eta \rightarrow 3\pi^0 \rightarrow 6\gamma$ with BR = 32%. Both decay modes allow straightforward measurements of complete angular distributions. The two-gamma mode is especially appealing because of the simplicity and ease in triggering and analysis. The invariant mass of the two-photon system is

$$\bar{m} = 2 \sin\left(\frac{1}{2}\chi\right) \sqrt{E_1 E_2}$$

where χ is the opening angle between the two photons; E_1 and E_2 are the energies of the two photons. For the Crystal Ball, the uncertainty in the opening angle is $\sim 4^\circ$, the error in $E_{1,2}$ is typically $\pm 3\%$; therefore, the uncertainty in measuring $\bar{m}$ at moderate eta energies is $\pm 4\%$. The resolution in the invariant mass of the η and in the missing mass of the undetected recoil is ample for obtaining a clean signal and a high background rejection.

III-7-B. N^* Spectroscopy

Fig. III-7-B1 shows the world data on $\sigma(\pi^- p \rightarrow \eta n)$ in the resonance region, compiled in Ref.[1]. Data that did not receive a "star" in this data base evaluation, because they were inconsistent, wrong, or incomplete, have been omitted. Only one PWA of the reaction $\pi^- p \rightarrow \eta n$ has been published [2]; unfortunately it is seriously in error because it is based on the incorrect data sets of Ref. [3]. Thus, for all practical purposes, there is little reliable information available on the η -decay amplitude of any N^* resonance, save to say that the so-called $S_{11}(1535)$ has a large branch to ηN . Based on various quark model calculations, we can expect the Crystal Ball to yield a rich harvest of information on the N^* resonances including some that have been predicted to exist but have never been observed.

Fig. III-7-B1 has some interesting features. Besides the broad first peak associated with the $S_{11}(1535)$ resonance with $\sigma_t \simeq 2.5$ mb, which may be a big peak plus a smaller satellite, there is a second big peak at $p_\pi = 1200$ MeV/c. This has an invariant mass of $\tilde{m} \simeq 1700$ MeV. There are several candidate resonances for this bump such as the $P_{11}(1710)$ which is a three-star state. The total $\pi^- p \rightarrow \eta n$ cross section is large here, ~ 1.2 mb. Finally, there is the third broad structure in $\sigma_t(\pi^- p \rightarrow \eta n)$ near $p_\pi = 2000$ MeV/c which implies $\tilde{m} \simeq 2.1$ GeV. Considering the high momentum, the total cross section is rather large, ~ 0.4 mb, which is 1.5% of $\sigma_t(\pi^- p)$. Possible candidates for this bump include the $S_{11}(2090)$, which has only one star, and the $P_{11}(2000)$, another one star candidate.

The bulk of nucleon spectroscopy information comes from $\pi^\pm p$ elastic scattering and CEX reactions. We plan to perform a thorough study of the $\pi^- p \rightarrow N^* \rightarrow n\eta$ differential cross section at many incident energies.

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III-7-C. Hyperon Spectroscopy

The experimental information on η production by K^- mesons is dismally small. Three ancient bubble chamber investigations exist for the reaction $K^- p \rightarrow \eta \Lambda$ and only one for $K^- p \rightarrow \eta \Sigma^0$. The existing data is shown in Figs. III-7-C1 [1] and III-7-C2 [2]. They corroborate the existence of the $S_{01}(1670)$ and $S_{21}(1750)$ resonances. The maximum total cross section for either reaction is a hefty 1 mb.

The η decay amplitudes of Λ^* resonances predicted by Koniuk and Isgur are given in Table III-7-C1. No η decay amplitudes of Σ^* resonances are given by these authors.

K^- photoproduction on a Λ or Σ^0 target may be measured via their inverse reactions $K^- p \rightarrow \Lambda \gamma$ and $K^- p \rightarrow \Sigma^0 \gamma$. Such measurements would nicely complement the CEBAF program on hyperon photoproduction on a proton target. The existing data consists of 258 events in the region of the $D_{03}(1520)$ Λ^* resonance [3], see Fig. III-7-C3. The cross section is surprisingly large, corresponding to $BR(D_{03} \rightarrow \Lambda \gamma) = 0.8\%$.

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TABLE III-7-C1 η decay of Λ^* resonances as calculated by Koniuk and Isgur. Not included are predictions for 12 unobserved Λ 's.

Λ^*	Resonance Mass (MeV)	Stars	$\eta\Lambda$ ampl. (GeV/c) ⁻¹	Comment
D ₀₃	1490	4	no	below thresh.
D ₀₃	1690	4	+0.1	—
D ₀₅	1815	4	-2.3	exp: (-)2±1
S ₀₁	1490	4	no	below thresh.
S ₀₁	1650	4	+2.2	exp: 2.8±0.7
S ₀₁	1800	3	-3.9	—
F ₀₅	1815	4	-0.7	exp: (-)1.2 ± 0.5
F ₀₅	2010	3	-1.6	—
F ₀₇	2070	1	+1.9	—
P ₀₁	1555	2	small	—
P ₀₁	1740	2	-1.3	—
P ₀₁	1860	-	+0.7	—
P ₀₃	1810	4	-1.8	—

III-7-D. The Completion of an η -Baryon Octet with $J^P = \frac{1}{2}^-$

In every case investigated thus far, the opening of the η channel is characterized by the formation of a strong S-wave resonance with a negative parity. This applies to $\pi^- p \rightarrow N^* \rightarrow \eta N$, to $K^- p \rightarrow \Lambda^* \rightarrow \eta \Lambda$, and to $K^- p \rightarrow \Sigma^* \rightarrow \eta \Sigma$. The Q-value of each resonance in the η decay channel is close to zero. The branching ratio of the η decay mode is much larger than expected on account of the smaller phase space vis-a-vis the π or K channel, see Table III-7-D1.

TABLE III-7-D1 Isobars with a well established η decay branch

PDT symbol	I, J^P	spectr. notation	mass (MeV)	η decay frac. (%)	Q (MeV)	R
N(1535)	$\frac{1}{2}, \frac{1}{2}^-$	S_{11}	$\sim 1483 \pm 16$	45-55	2 ± 16	$\eta N / \pi N \sim 1 \pm 0.5$
$\Lambda(1670)$	$0, \frac{1}{2}^-$	S_{01}	1670 ± 5	15-35	7 ± 5	$\eta \Lambda / \bar{K} N \sim 1 \pm 0.5$
$\Sigma(1750)$	$1, \frac{1}{2}^-$	S_{21}	1750 ± 20	15-55	10 ± 20	$\eta \Sigma / \pi \Sigma > 2$

PDT = Particle Data Table, Q is the energy release, e.g., $Q = M(S_{11}) - m_n - m_\eta$.
R is the ratio of branching ratios of the η and π (or K) decay modes.

We can expand Table III-7-D1 and consider the existence of a "new" Ξ -resonance, the $\Xi^*(1870)$, with spin $\frac{1}{2}$ and negative parity; the main decay mode is $\Xi^* \rightarrow \Xi + \eta$. It would fit the vacant place in the $(70, 1^-; S = \frac{1}{2})$ multiplet of SU(6). It could be produced in the reaction $K^- p \rightarrow K^+ \Xi^*(1870)$ at $p_K \simeq 2.3$ GeV/c.

The existence of an entire octet of η -baryons was first speculated on by Gyuk, Tuan, and Pakvasa [1,2]. Recently Tuan has focussed fresh attention on the subject suggesting that the discovery of the $\Xi^*(1870)$ is the smoking gun experimental test of such a special octet [3].

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Fig. III-7-B1 $\sigma_t(\pi^- p \rightarrow \eta n)$, the world one and two star data as discussed in Ref. [1]. The solid line is the fit to a Breit-Wigner type function.

Fig. III-7-C1 $\sigma_t(K^- p \rightarrow \eta \Lambda)$ at low energy.

Fig. III-7-C2 $\sigma_t(K^-p \rightarrow \eta\Sigma^0)$ at low energy. Fig. III-7-C3 $\sigma_t(K^-p \rightarrow \Lambda\gamma)$ at low energy.

IV-1 Search for the Eta-mesic Nucleus ${}^3_\eta\text{He}$

The production of eta mesons in the vicinity of the threshold in the primary reactions $\pi^- p \rightarrow \eta n$ and $\gamma p \rightarrow \eta p$ has been found to be an S-wave dominated process. It fulfills the Gell-Mann-Watson condition that the maximum orbital angular momentum ℓ should be limited by the inequality $\ell < \tilde{p}_\eta/mc$, where $\tilde{p}_\eta$ is the eta momentum in the c.m. For $\tilde{p}_\eta \leq 200 \text{ MeV}/c$, we obtain S-wave dominance. When the matrix element of the reaction is nearly constant, the energy dependence of the total cross section is given by the phase space dependence which implies $\sigma_t \sim \tilde{p}_\eta$ or $\sigma_t \sim \sqrt{\Delta T}$ where ΔT is the kinetic energy of the incident particle above the threshold energy.

In contrast to the $\pi^- p \rightarrow \eta n$ and $\gamma p \rightarrow \eta p$ reactions, the process $pd \rightarrow {}^3\text{He } \eta$ has a very different non-S-wave energy dependence, see Fig. IV-1-1. The angular distribution, however, is isotropic. This seemingly contradictory situation can be understood if the ${}^3_\eta\text{He}$ system is dominated by a quasi-bound or barely bound configuration. Because of the strong η -nucleon interaction in the S-state, this is actually a very plausible scenario. Such a quasi-bound ${}^3_\eta\text{He}$ state is a novel type of matter which we want to explore further. First, we want to make a precise measurement of the threshold $pd \rightarrow {}^3\text{He } \eta$ excitation function using a very thin target and the SPES II detector facility at Saturne. We also want to measure the excitation function of $d\sigma/d\Omega$ at 0° for $pd \rightarrow {}^3\text{He } \eta$. The corresponding curve at 180° has already been measured, see Fig. IV-1-2, and is dominated by a very narrow peak at threshold. It will be interesting to see if a similar narrow structure occurs at 0° which would be a clear manifestation of the existence of the novel ${}^3_\eta\text{He}$ state.

In the future, we would like to use the Crystal Ball multi-photon spectrometer (and therefore an excellent η detector) which we have proposed for installation at BNL to measure the absolute differential cross sections for $\pi^- {}^3\text{He} \rightarrow \eta {}^3\text{H}$ near threshold. By charge symmetry, we expect that ${}^3_\eta\text{He}$ has an isospin mirror state ${}^3_\eta\text{H}$.

Fig. IV-1-1 $\sigma_t(pd \rightarrow {}^3\text{He} \eta)$ measured at SPES II by the eta-collaboration (see Ph.D. thesis by R. Kessler, UCLA, unpublished)

Fig. IV-1-2 $d\sigma/d\Omega(pd \rightarrow {}^3\text{He} \eta)$ at 180° .

IV-2 Threshold π^0 Production in the Reaction $\vec{d}p \rightarrow {}^3\text{He} \pi^0$

π^0 production near threshold has been measured in the reaction $\vec{d} + p \rightarrow {}^3\text{He} + \pi^0$ with a beam of vector and tensor polarized deuterons using the SPES II spectrometer. This has yielded differential and total cross sections for 20 energies between threshold at $T_d = 397.2$ MeV and $T_d = 430$ MeV, as well as the analyzing powers $i T_{11}$, T_{20} , and T_{22} . The small background was due to the target walls.

The preliminary results are the following:

- (a) The total cross section rises nearly linearly with the c.m. η momentum, see Fig. IV-2-1; this is expected for S-wave production. The values are larger than the IUCF results which were obtained in a coincidence experiment detecting the ${}^3\text{He}$ with a spectrometer and a photon from the π^0 decay with a Cerenkov counter.
- (b) There is no evidence for a discontinuity in the slope of the total cross sections at the opening of the ${}^3\text{H} \pi^+$ channel at $T_d = 413$ MeV or $\vec{p}_{\pi^0} = 36.6$ MeV/c. This settles a fashionable speculation about a possible cusp effect.
- (c) The differential cross sections have a strong angular dependence, see Fig. IV-2-2; we have predicted the shape correctly in a simple two nucleon production model (see earlier Progress Reports) using the measured ${}^3\text{He}$ electromagnetic form factor as input.
- (d) The vector analyzing power $i T_{11}$ is consistent with zero in the forward direction and small, ~ 0.2 , in the backward direction, see Fig. IV-2-3.
- (e) The tensor analyzing power T_{20} is strongly negative and reaches the absolute minimum value, which is $-\sqrt{2}$, close to 0° , see Fig. IV-2-4.
- (f) The analyzing power T_{22} is compatible with zero, see Fig. IV-2-5.

Fig. IV-2-1 $\sigma_t(dp \rightarrow \pi^0 {}^3\text{He})$ measured in LNS Exp. #2/6.

Fig. IV-2-2 $d\sigma/d\Omega(dp \rightarrow \pi^0 {}^3\text{He})$ at 22 MeV above threshold.

Fig. IV-2-3 The vector analyzing power, $i T_{11}$, for $\bar{d}p \rightarrow \pi^0 {}^3\text{He}$.

Fig. IV-2-4 The tensor analyzing power, T_{20} .

Fig. IV-2-5 The analyzing power, T_{22} .

IV-3 Search for the Forbidden Decay $\mu^+ \rightarrow e^+ \gamma$

This is a large scale experiment to test lepton family number conservation now under way at LAMPF. It is assembled, tested, and operated by a collaboration of ten institutions. Our prime responsibility has been the development of the surface μ^+ beam with an intensity of $3 \times 10^7 \mu^+/\text{sec}$ and to construct the necessary equipment and analysis technique for measuring such an intensity. We have obtained two desirable beam tunes with the required intensity.

IV-4 Threshold η and η' Production by Electrons at CEBAF

The energy dependence of the cross section for eta meson photoproduction near threshold has been measured at ELSA by the UCLA-Bonn collaboration, see Section III-2. The photon energy resolution of the PHOENICS tagging system used in this experiment is $\sigma(E_\gamma) \approx 2.7$ MeV. The TAPS collaboration working at MAMI has made a similar measurement. Their preliminary results indicate that the resolution of the tagged photon energy was a little better, but it is not sufficient for a good determination of the electric dipole amplitude. The value of this is important for the understanding of the nature of the $S_{11}(1535)$ resonance and the determination of the position and width of the pole. The CEBAF photon tagger is not going to improve the energy resolution either. Near threshold, the cross section varies very rapidly: $\sigma_t \simeq 1.88\sqrt{\Delta E_\gamma} \mu b$, where ΔE_γ is the photon energy above η production threshold in MeV. This expression shows why a good knowledge of E_γ is crucial. We are exploring the use of the inelastic electron interaction, $e + p \rightarrow e' + p + \eta$. Incident and scattered electrons can be measured to good precision ($\delta E < 0.1$ MeV) giving a better measurement of the energy of the virtual photon.

We are fortunate that a suitable detector setup is being assembled at CEBAF in Hall C for a hypernuclear experiment. It consists of a dipole and two spectrometers to measure the recoil proton and scattered electron in coincidence.

Very little data on η' photoproduction exists. The cross section is much smaller than for η photoproduction as there is no suitable baryon resonance and the phase space factor is small due to the higher mass. If the electroproduction technique works as expected for η production, we plan to use it for η' production also.

PROGRAM V: *The Crystal Ball Detector*

V-1 Introduction

The SLAC Crystal Ball is a highly segmented, total energy electromagnetic calorimeter and multi-photon spectrometer, covering over 94% of 4π sterad. It consists of 2 major detectors: the ball proper and the charged particle tracker which is located on the inside of the ball. The ball, see Fig. V-1-1a, is constructed of 672 optically isolated NaI(Tl) crystals, each 15.7 radiation lengths (r.l.) thick. Each crystal is viewed by its own photomultiplier. The counters are arranged in a spherical shell with an inner radius of 25.3 cm and an outer radius of 66 cm. The shell has an entrance and exit tunnel for the beam, target plumbing, and tracker cables. An increase in the angular acceptance up to 98% is possible with the use of special endcaps. Electromagnetic showers in the ball are measured with an energy resolution of $\sigma/E = 2.7\%/[E(\text{GeV})]^{1/2}$. Shower directions are measured with a resolution in θ , the polar angle with respect to the beam axis, of $\sigma = 2^\circ - 3^\circ$ for energies in the range 50-500 MeV; the resolution in ϕ is $2^\circ/\sin \theta$. A Mercator-like projection of the crystal is shown in Fig. V-1-1b.

The crystal arrangement is based on the geometry of an icosahedron. Each of the 20 triangular faces ("major triangles") is divided into four "minor triangles" each consisting of nine individual crystals. Each crystal is shaped like a truncated triangular pyramid, 40.6 cm high, pointing towards the interaction point, with 5.1 cm long sides at the inner end and 12.7 cm long sides at the far end, see Fig. V-1-2. Each crystal is individually wrapped in reflector paper and aluminized mylar; it is viewed by a 5.1 cm phototube separated from the crystal by a glass window and a 5 cm air gap. The crystals are stacked to form two mechanically separate top and bottom hemispheres.

The charged particle tracker is constructed of four concentric cylindrical detectors surrounding the beam pipe. Each one consists of a double row of straw tubes with a diameter of 6.0 mm and 0.25 mm thick aluminum walls. The total number of tubes is 820. They are operated with a (79-20-1)% Ar-CO₂-CH₄ mixture. Layer 1 covers 98% and layer 4 74% of the solid angle, see Fig. V-1-3 and Table V-1-1. The resolution of the tracker is $\sigma_\phi = (1 - 2)^\circ$ and $\sigma_z = (1 - 2)\%$ of the tube length. The wall thickness of each chamber corresponds to 0.017 r.l. The beam pipe has a radius of 5.9 cm and is made of 1.5 mm aluminum which corresponds to 0.017 r.l.

The boundary between the two hemispheres is called the equator region. It is 0.8 cm thick consisting of 2×1.6 mm stainless steel; the rest is air. This introduces a less active space amounting to $< 16\%$ of the solid angle. The inner wall of the hemisphere is 1.5 mm stainless steel or 0.09 r.l.

TABLE V-1-1 Dimensions of the charged particle tracker

Layer	inner radius cm	active length cm	angle subtended by one tube	wire resist. Ω	acceptance %	# tubes
1	5.91	60.45	5.5°	292	98	2 × 64
2	7.10	45.21	4.6°	223	94	2 × 76
3	10.56	35.05	3.2°	177	84	2 × 122
4	14.32	32.51	2.4°	166	74	2 × 148

The Crystal Ball resides in a dry room to safeguard the hygroscopic NaI which is housed in the hermetically sealed hemispheres. The dry room maintains a constant temperature of $(20 \pm 1)^\circ \text{C}$ and a low humidity environment for the detector; the dew point is -42°C . Each hemisphere weighs about 3 tons and is housed in an elevator system to facilitate separating the two hemispheres up to 2 meters for easy access to the tracker.

The aperture at the smallest part of the entrance and exit tunnels has a half angle of 20° and a radius of 10.3 cm, allowing room for tagging and space for the liq. H_2 target plumbing and tracker cabling.

The efficiency for measuring photon energy is almost perfect and the high degree of crystal segmentation improves the resolution. Photons typically deposit 98% of their energy in a cluster of 13 crystals with a somewhat characteristic pattern. The thickness of the NaI amounts to about one hadron interaction length resulting in about 67% probability of pions interacting in the detector. The energy deposited by minimum ionizing particles is 197 MeV while the length of the counters corresponds to the stopping range of 233 MeV ($\mu^\pm$), 240 MeV ($\pi^\pm$), 341 MeV ($K^\pm$), and 425 MeV (p).

The phototubes are SRC L50 B01 selected for linearity over a wide range. The energy calibration is performed using the 0.661 MeV gammas from a ^{137}Cs source. A typical spectrum is shown in Fig. V-1-4. There is also available the 6.13 MeV gamma line from $^{10}\text{O}^*$ obtained from the reaction $^{10}\text{F}(p, \alpha)^{10}\text{O}^*$ using 0.4 MeV protons from a portable Van de Graaff accelerator.

The PMT analog pulses are sent to the counting house where they are integrated and held on capacitors for digitization. Data transfer is time consuming because all PMT's are read out sequentially.

Fast-out analog sums of 9 crystals corresponding to a minor triangle are available for trigger purposes. There are two independent hardware trigger systems, both using the fast-out analog signals from the ball. One is a tower trigger system which is a compact TTL logic system. It performs analog summations corresponding to various geometries in the ball such as 1) total ball energy or 2) a count of the number of major triangles with energy above some arbitrary threshold. The other trigger system is constructed from modular NIM logic and can make hardware analog sums for the top and bottom ball and full ball.

The present data acquisition limit on the event rate is 20 Hz. The dominant limitation on the event rate is due to the multiplexed sequential readout of the NaI crystals. Replacing this system with a fast, sparse readout system such as the CAMAC FERA system or FASTBUS would significantly improve the event recording rate, at least to ~ 500 Hz.

The linearity in the energy response of a Crystal Ball prototype over its exceptionally wide range is illustrated in Fig. V-1-5. The measured energy resolution is given in Fig. V-1-6. All figures are from Ref. [6].

There exists an extensive Monte Carlo program for the Crystal Ball and its tracker at DESY that includes all mechanical details. This can be adapted for the computers currently in use here.

Recently, we have proposed to move the Crystal Ball from its present storage location at SLAC to the AGS. Installation would first be in the C-8 line which provides $\pi^\pm$ and (separated) $K^\pm$ beams of good intensity up to $p = 760$ MeV/c. The Crystal Ball would be used for the η decay program, particularly to test C and CP invariance, as well as the "low energy" part of our new baryon spectroscopy program involving multi-photon final states. Measurements include $\pi^- p \rightarrow N^*$, with the N^* decaying into ηn , $\pi^0 n$, and γn final states. Furthermore, we plan to study $K^- p \rightarrow \Lambda^*$ with the Λ^* 's decaying into $\Lambda \eta$, $\Lambda \pi^0$, and $\Lambda \gamma$ final states. Of special interest is $K^- p \rightarrow \Sigma^0 \gamma$, which is inverse K^- photoproduction from an unstable target ($\tau(\Sigma^0) = 10^{-20}$ sec) which will complement the strangeness photoproduction program of CEBAF.

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Figure V-1-1 Schematic representations of the main detector. (a) Actual shape. (b) Mercator-like projection.

Figure V-1-2
Typical Crystal Ball crystal.

Figure V-1-4 Typical Ca^{137} spectrum.

Figure V-1-5
Test beam results from a Crystal Ball prototype.

Figure V-1-6
Crystal Ball resolution. Circles show test beam results from Crystal Ball prototype; boxes show resolutions from calibrations (Cs^{137} , Van de Graaff, and Bhabha); points with error bars show resolutions measured in this study. (Two high energy points overlap with Bhabha calibration.)

- (a) $R1 = 5.91 \text{ cm}$
 $R2 = 7.10 \text{ cm}$
 $R3 = 10.56 \text{ cm}$
 $R4 = 14.32 \text{ cm}$

Figure V-1-3. The layout of the charged particle tracker. (a) A partial cross section of the tracker, showing the layers of straw tubes. Each layer is 2 tubes thick, and actually covers the entire circumference around the beam axis; only a portion of the cross section is shown. (b) The packing of the straw tubes within one layer of the tracker. The second row of tubes fills the gaps left by the innermost row.

V-2 Upgrades of the Crystal Ball

We are considering some substantial upgrades. The first one is a new charged particle detection system with good angular resolution using drift chambers and scintillating fibers. Furthermore, we want to improve the beam and tagging system to obtain an eta production rate of $(1-4) \times 10^8 \eta/\text{day}$. This will require further sophistication of the electronics and data acquisition system. It will allow us to investigate many rare η decays at the BR level $(1-10) \times 10^{-11}$ in a reasonable length of time.

The most important upgrade, from the standpoint of detecting three-body decays to charged-particle final states such as $\eta \rightarrow \pi^0 e^+ e^-$ and $\eta \rightarrow \pi^0 \mu^+ \mu^-$, is the introduction of a magnetic field for momentum measurements with an accuracy of 2-4%. There are at least two schemes for this. In the first, the entire NaI ball without the phototubes is placed in a large volume 15 kG axial magnetic field parallel to the beamline. Such a field is produced by a large superconducting solenoidal magnet such as the SLAC HRS solenoid which is currently in use at LAMPF. Among other things, this would necessitate using long fiber light guides or photodiode-readout of the NaI counters.

Our favored method is to insert a compact magnetic analyzer in the beam pipe. Before the Crystal Ball appeared on the scene, we made conceptual design studies for a similar larger analyzer, which uses a novel design based upon the use of two small diameter superconducting solenoids in a Helmholtz coil arrangement [1]. It provides up to 70% acceptance for two-body charged particle decays and 35% acceptance for 3-body decays. A Monte Carlo calculation shows the acceptance for the decay $\eta \rightarrow \pi^0 \mu^+ \mu^-$ with detection of both muons and the two gammas from π^0 decay to be 18%. The design is ideally suited for modification of the Crystal Ball to provide additional momentum and tracking information on charged particles. The two coils could be inserted into the entrance and exit tunnels of the Crystal Ball as shown in Fig. V-2-1. This will require a reduction of the coil diameter from 40 or 30 cm, the values for which we did our design studies, to 20 cm. The gap size will correspondingly be reduced to 20 - 25 cm. Based on the results of our studies, we do not expect this to pose serious problems. The large iron frame shown in the figure provides a return path for the magnetic flux as well as mechanical support for the coils and detectors.

A cylindrically symmetric field is generated by the coils S_1 and S_2 connected in series. Figure V-2-2 shows the longitudinal field on the z axis as a function of z for a pair of standard solenoids and the field generated by a pair of solenoids using tapered coils. We have studied the various properties of this field in order to optimize its design. The graph indicates that the use of tapered coils reduces the volume in which a high field must be maintained to achieve the same field in the gap region. This reduces the stored energy by $\sim 40\%$. Since the cost of a superconducting solenoid goes roughly as $E^{0.66}$, this represents approximately 30% savings in cost.

We have also studied the forces such a field would generate on the coils. The direction of these forces depends strongly on the separation distance between the two

coils as well as between each coil and the iron return yoke. For a 2 cm gap here, the coils are attracted to the return yoke. This eliminates the need for a support mechanism between the coils but will require a structural support within the cryostat. This is possible with present technology. The tapered coil design reduces the magnitude of these forces by about 80% and simplifies the design of the structural support for the coils. These forces do not present any serious problems in the case of a quench of one or both coils.

The momentum resolution obtainable from such a field is of the order of 2%. This value is a combination of the resolution of the charged particle tracking and the uncertainty in the initial radial position of a trajectory; it is dominated by the latter. For more dispersed beams, such as secondary pion beams, this initial position is determined by beam particle tracking which gives the target interaction vertex. Precise wire chambers or scintillating fiber arrays with $\approx 100 \mu\text{m}$ resolution can be used to provide the tracking information for both the beam particles and the charged eta decay products. With the use of precision wire chambers, we expect that we will be able to keep the nominal field at the design value of 1.5 T or even reduce it to approximately 1 T, though the radius of the solenoids will be reduced from 40 cm to 20 cm. This significantly reduces the design constraints and cost.

Several minor modifications of the magnet design and the Crystal Ball will be necessary in order to implement this design. Firstly, the large return yoke for the field will have to be mounted horizontally instead of vertically, requiring a support structure. This is due to the fact that the Crystal Ball opens vertically to gain access to the target area. Another option would be to construct an asymmetric yoke in which the top return loop is removed. This may be possible since a reduced field can be used.

Another possible modification requires the removal of the photomultiplier tubes from the NaI crystals if they cannot be shielded sufficiently from the stray magnetic field coming from the solenoid gap. They would only need to be moved to a region near the yoke where the field is relatively small. Fiber optic light guides can be used to connect the tubes to the crystals. The tubes will still move with the crystals during opening of the ball, so this is not a severe constraint.

Monte Carlo studies still need to be done to measure quantitatively the improvement such a modification would provide for the Crystal Ball spectrometer. Design studies also need to be done to understand the details such a modification would entail; in principle, there appears no major obstacle preventing it. We know that the construction of the solenoid geometry is feasible with present technology. Details are given in Refs. [1-4]. Tagging will likely be done using $\pi^+ d \rightarrow pp\eta$ as the η production process.

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Figure V-2-1: Schematic design of the split solenoid arrangement within the Crystal Ball. The tagger and the tracking detectors are not shown.

Figure V-2-2: Axial field (B_z) of a pair of solenoids, calculated on the solenoid axis. The upper curve is for standard magnet design, the lower curve for tapered solenoids

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- UN-48 *$\eta \rightarrow \gamma\gamma$ Analysis Status Report I*, D. White - September 1998

**Colloquia, Seminars, and Invited Talks at International
Conferences and Workshops**

1990

February 7	LAMPF, <i>Charge Symmetry Breaking and the Mass of the Quarks</i>
March 23	Karlsruhe, <i>Charge Symmetry Breaking and the Determination of the u-d Quark Mass Difference</i>
March 26	SEPN Saclay, <i>The PILAC and SCRUNCHER at LAMPF</i>
April 26	UCLA, <i>Workshop on Testing CPT and Studying CP Violation at a ϕ Factory, Summary on Quark Physics</i>
June 14	LAMPF PILAC Workshop, <i>Nuclear-Particle Physics with PILAC</i>
July 25	Novosibirsk, <i>Charge Symmetry Breaking and the Determination of the Down-Up Quark Mass Difference</i>
August 3	IUCF, <i>New Perspectives on Charge Symmetry</i>
September 12	SEPN Saclay, <i>The QCD Perspective of Charge Symmetry</i>
September 17	Institut für Kernphysik der KFA Jülich, <i>The Modern View of Charge Symmetry</i>
October 12	UCLA, <i>Phi Factory Consortium Meeting, Quark Physics</i>

1991

May 8	Krakau (Poland) COSY Meson Physics Workshop, <i>Rare Meson Decays</i>
May 24	Tucson (Arizona), 4th Conference on International Particle-Nuclear Physics, <i>Forbidden, Rare and Not-So-Rare Eta Decays</i>
June 7	UCLA, ϕ Factory Detector Workshop, <i>Fascinating Decays of Light Mesons</i>
June 24	University of Bonn (Germany), <i>The Fascinating World of Rare Meson Decays</i>
July 1	Dubna (USSR), <i>Rare Decays of Light Mesons</i>

Colloquia, Seminars, and Invited Talks at International
Conferences and Workshops

1991

- September 10 Bad Honnef (Germany), IV Int. Symp. on πN Physics,
 Threshold η Production
- September 12 Jülich (Germany), Institut für Kernphysik der KFA Jülich,
 Threshold Meson Production
- October 7 Brookhaven National Lab, N.Y., *Rare Decays of the Eta*
- December 4 UCLA Experimental Particle Physics Seminar,
 The Wonderful World of the Forbidden Eta Decays

1992

- March 25 LAMPF, *The First Physics Results from the Saclay
 Eta-Meson Factory*
- April 7 LNS (France), *Testing C and CP*
- April 10 Jülich (Germany), Institut für Kernphysik der KFA Jülich,
 Testing C and CP
- April 16 CERN (Geneva), *η -Meson Decays and the Search for New Physics*
- June 17 CEBAF Workshop, *Electroproduction of Light Mesons near Threshold*
- July 15 Argonne National Laboratory, *New Role of the η in Nuclear
 and Particle Physics*
- July 16 Fermi Laboratory, *New Tests of CP*
- August 5 VPI, πN Workshop, *The $\pi^- p \rightarrow \eta n$ Data Base*
- October 14 APS, Santa Fe Workshop on New Vistas in Physics with High
 Energy Pion Beams, *η Physics*
- November 13 APS - DPF 1992, Fermi Laboratory, *ETA Physics*

Colloquia, Seminars, and Invited Talks at International
Conferences and Workshops

1993

February 4	Bad Honnef (Germany) 105. WE-Heraeus-Seminar,
Hadronic Processes at Small Angles in Storage Rings,
<i>η Production</i>
March 4	BNL, Future Directions in Particle and Nuclear Physics,
<i>What is so Special about η Physics?</i>
March 7	BNL, Future Directions in Particle and Nuclear Physics,
D-line Working Group, <i>Hyperon Hunting with η-Mesons</i>
March 17	UCLA, Joint Nuclear/Experimental Particle Physics
Journal Club, <i>Eta Physics</i>
June 10	SLAC, SLAC Experimental Seminar, <i>Testing C and CP
with the Crystal Ball</i>
August 3	BNL, Physics Colloquium, <i>Tests of Fundamental Symmetries
with the Eta Meson</i>
September 5	U. of Colorado, Boulder, 5th Meson-Nucleon Symposium
<i>Baryon Spectroscopy with η Mesons</i>

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**Organization Committees of
International Conferences and Workshops**

Paris 90

7th Conference on Polarization Phenomenon in Nuclear Physics

Paris, July 9-13, 1990

Session Chairman on July 12

Particle Production near Threshold

Topical Conference IUCF, September 30-Oct. 3, 1990

Member of the International Program Committee

**IVth International Symposium on Pion-Nucleon Physics and
the Structure of the Nucleon**

Bad Honnef, Germany September 9-13, 1991

Advisory Committee

Session Chairman

Baryon Spectroscopy and the Structure of the Nucleon

Saclay, France September 23-25, 1991

Session Chairman

Hadronic Processes at Small Angles in Storage Rings

Bad Honnef, Germany February 4-6, 1993

Session Chairman

**Future Directions in Particle & Nuclear Physics at Multi-GeV Hadron
Beam Facilities**

Brookhaven National Laboratory March 4-6, 1993

Co-Organizer of the section on η -Physics**Vth International Symposium on Pion-Nucleon Physics and
the Structure of the Nucleon**

Boulder, Colorado September 6-10, 1993

International Advisory Committee Session Chairman

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