The Meson Physics Laboratory enters the international collaboration performing the Program entitled "Baryon and Hyperon Spectroscopy with the Crystal Ball". This collaboration was formed finally in 1995–1997, it included 14 institutions from 5 countries. Experiments E913/914/953/958 were carried out in the C6 line of the Alternating Gradient Synchrotron at Brookhaven National Laboratory and involves following items:

1. Measurement of the differential cross sections of $\pi^- p$ reactions with neutral particles in the final state ($\pi^- p \to \gamma n$, $\pi^- p \to \pi^0 n$, $\pi^- p \to \eta n$, $\pi^- p \to \pi^0\pi^0 n$.) at the incident pions momenta from 159 to 750 MeV/c – experiments E913/958.

2. Measurement of the differential cross sections of $K^- p$ reactions with neutral particles in the final state: $K^- p \to \gamma\Lambda$, $K^- p \to \pi^0\Lambda$, $K^- p \to \eta\Lambda$ and analogous reactions with the production of Σ^0 hyperon – experiments E914/953.

3. Study of rare and forbidden decays of η meson.

Owing to the use of a multiphoton 4π total absorption spectrometer Crystal Ball, the cross sections of all ($\pi^- p$ reactions (or $K^- p$ reactions) with neutral particles in the final state were measured simultaneously by detecting gammas arisen directly in the reactions or after the decay of produced neutral mesons or hyperons. The ball proper is a sphere with an entrance and exit opening for the beam and an inside cavity for the target. It is constructed of 672 optically isolated NaI(Tl) crystals which are shaped like a truncated triangular pyramid. An external diameter of the Crystal Ball is 132 cm, an inner diameter of the NaI(Tl) crystals layer is 50 cm. The thickness of individual NaI(Tl) crystal is 15.7 radiation lengths. An electromagnetic shower from a single photon deposits energy in several crystals, called a cluster. The present cluster algorithm sums the energy from the crystal with the highest energy with that from the twelve nearest neighbors. Shower directions are measured with the resolution in polar angle $\sigma_\theta = 2^\circ$–3° for energies in the range 50–500 MeV; the resolution in azimuthal angle is $\sigma_\varphi = 2^\circ/\sin\theta$. The energy resolution was $\sigma_E/E = 2.0\%/E^{0.36}$ with E given in GeV

a) Study of $\pi^- p$ reactions with neutral mesons in the final state

A series of experiments on studying reactions $\pi^- p \to$ *neutrals* was performed using a liquid hydrogen target at 22 energies of the incident pions in the range from 65 to 625 MeV (corresponding pions momenta are from 150 to 750 MeV/c). This energy range covers one Δ $P_{33}(1232)$ resonance and three N^* resonances: the $P_{11}(1440)$, the $D_{13}(1520)$ and the $S_{11}(1535)$. At each energy an additional measurement with an empty target was done.

When studying $\pi^- p$ charge exchange scattering $\pi^- p \to \pi^0 n$ two-cluster events were used for selecting this reaction and obtaining differential cross sections. For such events $\gamma\gamma$ invariant mass was calculated in an assumption that both clusters are originated by photons. If the value of this invariant mass coincided with the mass of π^0 meson and the kinematic relations of the reaction under study were fulfilled, such events was assumed to be caused by the reaction $\pi^- p \to \pi^0 n$. For each event the angle θ^{cm}, at which π^0 meson was produced in the centre-of-mass system, was calculated, and then the whole set of obtained data was divided into 20–25 bins in $\cos\theta^{cm}$. After that the data obtained in measurements with the empty target were subtracted from the "hydrogen" data, and in each angular bin the differential cross section was calculated (needed for these calculations angular acceptance was determined on the basis of the Monte Carlo simulation of the experiment). Processing of obtained data sets with the goal to extract the cross sections of $\pi^- p$ charge exchange scattering was performed mainly by PNPI scientists.

At the incident pions momenta higher than the η-production threshold accumulated data were used to obtain cross sections of the reaction $\pi^- p \to \eta n$. Until now existing experimental information on the cross sections of this reaction has been very scarce and contradictory, especially near the threshold. At the same time, obtaining accurate experimental data in the near-threshold region is very important for verifying theoretical models of the η-meson production. Such data will also be useful for extracting the ηN scattering length and understanding properties of the $S_{11}(1535)$ resonance. The differential and total cross sections of the reaction $\pi^- p \to \eta n$ were determined in the momentum range from the threshold (685 MeV/c) up to 750 MeV/c. Events attributed to the reaction $\pi^- p \to \eta n$ were selected by detecting photons from the η-meson decays $\eta \to 2\gamma$ or $\eta \to 3\pi^0$. Obtained new results are in a good agreement with those of earlier experiments but exceed significantly all existing experimental data in a statistical accuracy.

In 2002, another run was performed using a polyethylene (CH_2) target. The experiment was carried out at ten incident pions momenta covering the range from 695 to 750 MeV/c. To exclude a background due to interactions of the incident pions with carbon nuclei of this target, at every energy an additional measurement was made using a carbon (graphite) target of corresponding thickness. In a subsequent off-line analysis, data obtained with the carbon target were subtracted from CH_2 data – after the appropriate renormalization of monitor counts. An analysis of data obtained is underway now with the aim to extract absolute values of the differential cross sections of the reactions $\pi^- p \to \pi^0 n$ and $\pi^- p \to \eta n$.

b) Study of $K^- p$ reactions with neutral particles in the final state

In experiments on studying $K^- p$ reactions, negative kaons were separated from pions, muons and electrons using two $\boldsymbol{E} \times \boldsymbol{B}$ separators and the time-of-flight technique. Experimental data on $K^- p$ reactions were taken at two different central beam momenta. The low- and high-momentum beams had the central momenta of 720 MeV/c and 750 MeV/c, respectively. The beam wire chambers of the magnetic spectrometer placed at the exit of meson channel were used to measure the momentum difference of every kaon with respect to the central value. An accuracy of the absolute K^- momentum is ± 2.5 MeV/c. Both the low- and high-momentum beam were tuned to optimize the *K/p* ratio and the beam position on the liquid hydrogen target. We obtained about 8×10^4 kaons in an AGS beam spill of 2.8 s duration every 5 s with the *K/p* ratio about 1:10.

When studying the $K^- p \to \eta\Lambda$ reaction, the final state was identified in two ways: (i) *via* the $\eta \to 2\gamma$ and $\Lambda \to \pi^0 n \to 2\gamma n$ decays (four-cluster events); (ii) *via* $\eta \to 3\pi^0 \to 6\gamma$ and $\Lambda \to \pi^0 n \to 2\gamma n$ decays (eight-cluster events). Our new data have much better precision than previous measurements which were very scarce and contradictory and did not allow to determine even a shape of the total cross section momentum dependence.

There are many similarities between the $K^- p \to \eta\Lambda$ reaction and the $\pi^- p \to \eta n$ reaction near the threshold, which is dominated by the $N(1535)1/2^-$ resonance. These include:

1. The steep rise in σ_{tot} at the opening of the η channel.
2. *s*-wave dominance with similar slope parameters of the σ_{tot} dependence on η c.m. momentum:

$$\sigma_{tot}(K^- p \to \eta\Lambda) = (17 \pm 3)(\mu b/(MeV/c)) \times p^*_\eta,$$

$$\sigma_{tot}(\pi^- p \to \eta n) = (15 \pm 1)(\mu b/(MeV/c)) \times p^*_\eta.$$

3 Large values for σ_{tot} far from the opening of the η channel; the maximum value for $\sigma_{tot}(K^- p \to \eta\Lambda)$ is 1.5 ± 0.1 mb with p^*_η = 81 MeV/c, while for $\sigma_{tot}(\pi^- p \to \eta n)$ the maximum value is 2.6 ± 0.3 mb with p^*_η = 182 MeV/c.

To understand the near-threshold η production, we assumed that it is dominated by the excitation of the intermediate $\Lambda(1670)1/2^-$ resonance with very minor contribution from the $\Lambda(1600)1/2^+$ and $\Lambda(1690)3/2^-$ states. To fit the total cross section, a unitarity multi-channel parametrization was applied. The fitted mass of the $\Lambda(1670)1/2^-$ resonance, $M = 1673 \pm 2$ MeV. This new value of mass is consistent with the most recent results listed in the Review of Particle Physics.

c) Study of rare and forbidden η-meson decays

The Crystal Ball collected ~ 30 million η mesons from the reaction $\pi^- p \to \eta n$ using a liquid hydrogen target at the incident pions momentum of 720 MeV/c. Data processing is being performed in USA and at PNPI. An important goal of this experiment was to improve the present values of branching ratios for rare and forbidden decays of the η meson. The following neutral decay modes were investigated using the Crystal Ball: $\eta \to 3\gamma$, $\eta \to \pi^0\gamma$, $\eta \to 2\pi^0\gamma$, $\eta \to 3\pi^0\gamma$, $\eta \to 4\pi^0$, $\eta \to \pi^0\gamma\gamma$, $\eta \to \pi^0\pi^0\gamma\gamma$.

The decay $\eta \to 3\gamma$ is forbidden by C invariance. Besides, there exist several additional factors which suppress this decay. The decay to three photons is an electromagnetic interaction of the 3rd proportional to $\alpha^3 \approx 4 \times 10^{-7}$. The decay is suppressed even more by the limitations of the phase space and by centrifugal barrier. The upper limit for this decay measured in this experiment for the first time is $BR(\eta \to 3\gamma) < 4 \times 10^{-5}$ at the 90% CL. Candidates for the $\pi^- p \to \eta n \to 3\gamma n$ process were searched for in the three-cluster data set, which comprised 18.4×10^6 events. The mostly significant experimental background is due to the decay $\eta \to 3\pi^0 \to 6\gamma$, when photon showers overlap in the detector.

A spin-zero to spin-zero transition by the emission of a real photon is forbidden by conservation of angular momentum. Thus, the decay mode $\eta \to \pi^0\gamma$ should be absolutely forbidden. Furthermore, this decay is not allowed by gauge invariance and by C invariance. Possible candidates for the $\pi^- p \to \eta n \to \pi^0\gamma n \to 3\gamma n$ process were searched for in the same three-cluster data set that was used for the determination of the upper limit in $BR(\eta \to 3\gamma)$. This process has the same background sources as the $\pi^- p \to \eta n \to 3\gamma n$ process. The number of effective constraints that apply to the $\pi^- p \to \pi^0\gamma n \to 3\gamma n$ hypothesis is one more than for $\pi^- p \to 3\gamma n$, namely the mass of the π^0 meson. The obtained upper limit $BR(\eta \to \pi^0\gamma) < 9 \times 10^{-5}$ at the 90% CL is about two times larger than the one for $BR(\eta \to 3\gamma)$.

The decay modes $\eta \to 2\pi^0\gamma$ and $\eta \to 3\pi^0\gamma$ are strictly forbidden both by charge conjugation invariance. The five-cluster data set of 5.2×10^6 events was used to search for $\pi^- p \to \eta n \to 2\pi^0\gamma n \to 5\gamma n$ candidates. The background for this decay is determined mainly by evens from the decay $\eta \to 3\pi^0$ in cases when two single-photon showers overlap or one photon is not detected in the Crystal Ball. Another source of background is the reaction $\pi^- p \to 2\pi^0 n$ when either a single-photon splits off or the neutron is detected in the Crystal Ball. The obtained upper limit is $BR(\eta \to 2\pi^0\gamma) < 5 \times 10^{-4}$ at the 90% CL. Using the value $\Gamma(\eta \to all) = 1.29 \pm 0.07$ keV, the BR was converted to the decay-width upper limit: $\Gamma(\eta \to 2\pi^0\gamma) < 0.64$ eV. No searches for this decay mode have been reported earlier. To search for the reaction $\pi^- p \to \eta n \to 3\pi^0\gamma n \to 7\gamma n$ the sample of seven-cluster events was used, which has 0.168×10^6 entries. The main source of background here is $\eta \to 3\pi^0 \to 6\gamma$ events with seventh cluster produced by a one-photon shower split-off or an occasional cluster from a pile-up event. To suppress this background, the several selection cuts were applied. The obtained upper limits are $BR(\eta \to 3\pi^0\gamma) < 6 \times 10^{-5}$ at the 90% CL and $\Gamma(\eta \to 3\pi^0\gamma) < 0.077$ eV.

The decay $\eta \to 4\pi^0$ is forbidden by CP conservation, so it provided a test for strong CP-violating amplitudes down to a level of about 10^{-7} where weak interactions come into play. This decay mode requires eight neutral clusters in the Crystal Ball which must be reconstructed to four π^0 mesons which together have the invariant mass of the η meson. This enables also to eliminate the expected background from the $\eta \to 3\pi^0$ decay in which there are two extra clusters from photon showers which breakup into separate clusters. The main limitation of the $4\pi^0$ decay mode is its small phase space, the maximum π^0 momentum in $\eta \to 4\pi^0$ is only 39 MeV/c, as compared to the π^0 momentum in $\eta \to 2\pi^0$ of 238 MeV/c. The eight-cluster data set contained 14804 experimental events. These events were subjected to a constrained least square fit satisfying the $\pi^- p \to \eta n \to 4\pi^0 n \to 8\gamma n$ reaction hypothesis with a confidence level > 2% With no eight-cluster event from $\eta \to 4\pi^0$ found, the upper limits become $BR(\eta \to 4\pi^0) < 6.9 \times 10^{-7}$ at the 90% CL and $\Gamma(\eta \to 4\pi^0) < 8.3 \times 10^{-4}$ eV.

All above considered decays of the η meson are forbidden – in the framework of the Standard Model – by the fundamental conservation laws, and a stimulus for the investigation of branching ratios of such decays is the search for such decay mechanisms which were outside the Standard Model. However, there is another category of decays (so called rare decays) values of branching ratios for which are predicted by existing theoretical models, and experiments on measuring these branching ratios are important for testing these models. The η-meson decays $\eta \to \pi^0\gamma\gamma$, $\eta \to \pi^0\pi^0\gamma\gamma$ belong just to this category. The decay mode $\eta \to \pi^0\gamma\gamma$ is forbidden in leading order of a χPTh momentum expansion because there is no direct coupling of photons to π^0 and η mesons. The second order is much suppressed because it involves G-parity violating transitions. And only third and more high order give a contribution to the decay amplitude. Thus we have the unique test that the decay rate for $\eta \to \pi^0\gamma\gamma$ is a direct test of the corretness of calculations of the third order χPTh, the first order being zero and the second order being very small. The experimental determination of the $BR(\eta \to \pi^0\gamma\gamma)$ is a rather complicated task, mainly because of the contribution of background from the decay $\eta \to 3\pi^0 \to 6\gamma$ and the reaction $\pi^- p \to 2\pi^0 n \to 4\gamma n$. As a result of multi-step procedure of processing four-cluster data set about 1600 events attributed to the decay $\eta \to \pi^0\gamma\gamma$ were obtained. This gives $BR(\eta \to \pi^0\gamma\gamma) = (3.5 \pm 0.7_{stat} \pm 0.6_{syst}) \times 10^{-4}$ and $\Gamma(\eta \to \pi^0\gamma\gamma) = 0.45 \pm 0.09_{stat} \pm 0.08_{syst}$ eV. This result agrees well with the theoretically calculated value $\Gamma(\eta \to \pi^0\gamma\gamma) = 0.47 \pm 0.10$ eV but lower by a factor of 2 in comparison with the experimental value obtained in 1982 at the setup GAMS.

There are χPTh theoretical predictions for the probability of the decay $\eta \to \pi^0\pi^0\gamma\gamma$, but estimations of the BR values given by theoreticians are too low (at a level of 10^{-6}–10^{-7}) to be confirmed or rejected on the base of existing experimental data. For the time present, an analysis of data obtained using the Crystal Ball has given only the upper limit for the BR of this decay: $BR(\eta \to \pi^0\pi^0\gamma\gamma) < 1.2 \times 10^{-3}$.