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Pion Polarizabilities and Hybrid Meson Structure at CERN COMPASS

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Abstract:

CERN COMPASS [1] can investigate pion-photon interactions, to achieve a unique Primakoff Coulomb physics program, centered on pion polarizability and hybrid meson structure studies [2, 3, 4, 5]. COMPASS uses 100-280 GeV beams (μ, π) and a virtual photon target, and magnetic spectrometers and calorimeters to measure the complete kinematics of pion-photon reactions. The COMPASS experiment is scheduled to begin data runs in 2001. Pion polarizabilities and hybrid mesons can be studied via the Primakoff reactions $\pi^-\gamma \to \pi^{-\prime}\gamma$ and $\pi^-\gamma \to Hybrid$. The electric ($\bar{\alpha}$) and magnetic ($\bar{\beta}$) pion and Kaon polarizabilities characterize their deformation in an electromagnetic field, as occurs during $\gamma\pi$ Compton scattering. They depend on the rigidity of their internal structures as composite particles, and are therefore important quantities to test the validity of theoretical models. The polarizability measurement will provide an important new test of QCD chiral dynamics. The studies of quark-antiquark-gluon hybrid mesons would improve our understanding of these exotic mesons. COMPASS may improve previous Primakoff polarizability and Hybrid studies by two to three orders of magnitude.

Appendixes A (Pion and Kaon Polarizabilities at COMPASS) and B (Hybrid Meson Structure at COMPASS) of this contribution include evaluations submitted to the APS DNP Town Meeting White Paper Committee. These summarize (1) the fundamental scientific issues addressed, (2) major achievements since the last DNP long range plan, (3) the short and long term U.S. outlook, (4) comparison of U.S. and global effort, (5) other issues.

1. Pion-Photon Interactions:

Pion polarizabilities and hybrid meson structure can be studied via pion-photon interactions. Appendixes A and B of this contribution include global evaluations on these subjects submitted to the APS DNP Town Meeting White Paper Committee. The scientific background for these subjects is described below.

Pion Polarizabilities

For pion polarizability, $\gamma\pi$ scattering was measured (with large uncertainties) with 40 GeV pions [6] via radiative pion scattering (pion Bremsstrahlung) in the nuclear Coulomb field: $\pi + Z \to \pi' + \gamma + Z'$. In the planned COMPASS, version of this experiment, pion

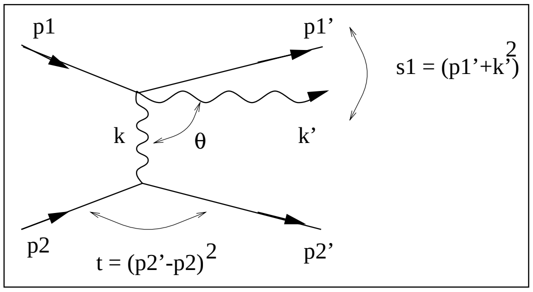

Figure 1: The Primakoff γ-hadron Compton process and kinematic variables (4-momenta): p1, p1$'$ = for initial/final hadron, p2, p2$'$ = for initial/final target, k, k$'$ = for initial/final gamma, and θ the scattering angle of the γ in the alab frame.

polarizability events have a stiff pion at angles smaller than 0.5 mrad, very close to the non-interacting beam, and a single forward photon at angles smaller than 2 mrad. The kinematic variables for the pion polarizability Primakoff process are shown in Fig. 1. A virtual photon from the Coulomb field of the target nucleus is scattered from the pion and emerges as a real photon accompanying the pion at small forward angles in the laboratory frame, while the target nucleus (in the ground state) recoils with a small transverse kick p$_t$. The peak at small target p_t used to identify the Primakoff process is precisely measured off-line using the beam and vertex detectors. The radiative pion scattering reaction is equivalent to γ + π^- $\rightarrow$ γ + π^- scattering for laboratory γ's of order 1 GeV incident on a target π^- at rest. It is an example of the well tested Primakoff formalism [7, 8] that relates processes involving real photon interactions to production cross sections involving the exchange of virtual photons.

For the $\gamma\pi$ interaction at low energy, the χPT effective Lagrangian establishes relationships between different processes. For example, using data from radiative pion beta decay, χPT predicts the pion polarizabilities [9, 10]: $\bar{\alpha}_\pi$ = -$\bar{\beta}_\pi$ = 2.7 ± 0.4, expressed in units of 10^{-43} cm^3.

The pion polarizabilities deduced by Antipov et al. [6] in their low statistics experiment ($\sim$ 7000 events) were $\bar{\alpha}_\pi = -\bar{\beta}_\pi = 6.8 \pm 1.4 \pm 1.2$. It was assumed in the analysis that $\bar{\alpha}_\pi + \bar{\beta}_\pi = 0$, as expected theoretically [10]. The deduced polarizability value, ignoring the large error bars, is about three times larger than the χPT prediction. **The available polarizability results [11] have large uncertainties. There is a clear need for the new and improved radiative pion scattering data from COMPASS.**

New COMPASS data will be compared also to new Mainz data. At MAMI-B at Mainz, measurements [12] and calculations [13] are under way of $p(\gamma, n\pi^+\gamma')$ radiative pion photoproduction reaction on the proton. The elastic $\gamma\pi^+$ scattering cross section can be found by extrapolating such data to the pion pole. This corresponds to "Compton" scattering of gamma's from virtual π^+ targets in the proton, and therefore also allows a measure of the pion polarizability. The experiment is running with 500-800 MeV tagged photons, with detection of γ', neutron, and charged pion in coincidence. For the long term, a pion polarizability experiment with polarized tagged photons was proposed [14], associated with the proposed JLab 12 GeV upgrade.

Hybrid Mesons

The hybrid ($q\bar{q}g$) mesons, along with glueballs (gg) are some of the most interesting consequences of the non-Abelian nature of QCD. The unambiguous confirmation of hybrid states will be a major event in hadron spectroscopy. Hybrids contain explicit glue as opposed to hidden glue in conventional hadrons. Understanding explicit glue is critical, considering that most of the mass around us is made of gluons. For the understanding of confinement, it is of major importance and relevance to establish the existence of hybrid mesons and to study their structure. Input from experiments is needed to guide us to better understanding. Evidence from completely different experiments are needed to show that the present evidence is not the result of some incorrectly interpreted artifice. We may look forward to comparisons of new COMPASS and JLab [15, 16, 17] hybrid meson experiments.

Detection of these exotic states is a long-standing experimental puzzle. The most popular approach for hybrid searches is to look for the 'oddballs'—mesons with quantum numbers not allowed for ordinary $q\bar{q}$ states. For Primakoff/diffractive production, the 'oddball' mesons for $J \leq 2$ are: $I^G(J^{PC}) = 1^-(1^{-+})$ 'π_1'—or more generally $I^G(J^{PC}) = 1^+(0^{+-})$ 'b_0' or $I^G(J^{PC}) = 1^+(2^{+-})$ 'b_2'—hybrids. The signature for such a state is when a detailed partial wave analysis (PWA) of a large data sample requires a set of quantum numbers which is inconsistent with a regular (q-qbar) meson.

Barnes and Isgur, using the flux-tube model [18, 19], calculated the mass of the lightest gluonic hybrid to be around 1.9 GeV, with the quantum numbers of $J^{PC} = 1^{-+}$. Close and Page [20] predict that such a gluonic hybrid should decay into the following channels:

$b_1\pi$	$f_1\pi$	$\rho\pi$	$\eta\pi$	$\eta'\pi$
170	60	$5 \rightarrow 20$	$0 \rightarrow 10$	$0 \rightarrow 10$

where the numbers refer to the partial widths in MeV. They expect its total width to be larger than 235-270 MeV, since the $s + \bar{s}$ decay modes were not included. Recent updates on hybrid meson structure are given in Refs. [21, 22, 23]

From more than a decade of experimental efforts at IHEP [24, 25, 26], CERN [27, 28], KEK [29], and BNL [30], several hybrid candidates have been identified. More recently, BNL E852 [30] reported two $J^{PC} = 1^{-+}$ resonant signals at masses of 1.4 and 1.6 GeV in $\eta\pi^-$ and $\eta\pi^0$ systems, as well as in $\pi^+\pi^-\pi^-$, $\pi^-\pi^0\pi^0$, $\eta'\pi^-$ and $f_1(1285)\pi^-$. The VES collaboration presented [31] the results of a coupled-channel analysis of the $\pi_1(1600)$ meson in the channels $\rho\pi$, $\eta'\pi$ and $b_1(1235)\pi$. Their results, and those of the crystal barell collaboration [28], are consistent with the BNL results.

The kinematic variables for the $\pi\gamma \rightarrow HY \rightarrow \pi^-\eta$ Primakoff process in COMPASS are shown in Fig. 2. A virtual photon from the Coulomb field of the target nucleus interacts with the pion, a Hybrid meson is produced and decays to $\pi^-\eta$ at small forward angles in the laboratory frame, while the target nucleus (in the ground state) recoils coherently with a small transverse kick p$_T$. The peak at small target p_T used to identify the Primakoff process is measured off-line using the beam and vertex detectors.

The partial-wave analysis (PWA) of systems such as $\eta\pi$ or $\eta'\pi$ in the mass region below 2 GeV requires care and experience. This is so because (1) this region is dominated by the strong 2^+ 'background' (a_2 resonance), and (2) that the PWA may give ambiguous results [25] for the weaker 1^{-+} wave. For Primakoff production, the hybrid production cross section may increase relative to the close lying a_2 state, considering the estimated radiative widths. These are $\Gamma(a_2 \rightarrow \pi\gamma) = 300$ keV, and $\Gamma(\pi_1 \rightarrow \pi\gamma) \approx 90 - 540$ keV, as discussed in Section 3. This may significantly diminish the partial wave analysis uncertainties of non-Primakoff production experiments for the 1^{-+} wave. Furthermore, in Primakoff (photon exchange) and diffractive (glue-rich pomeron exchange) hybrid production, meson exchange backgrounds and final state interactions are strongly suppressed, which is an important advantage compared to previous $\pi^- p \rightarrow Hybrid$ production experiments.

For both BNL E852 and VES data, it is not known what Regge exchanges are responsible for the production of the $J^{PC} = 1^{-+}$ exotic states at 1.4 and 1.6 GeV, Both the $a_2(1320)$ and the exotic waves are produced via natural-parity exchanges which include the Pomeron.

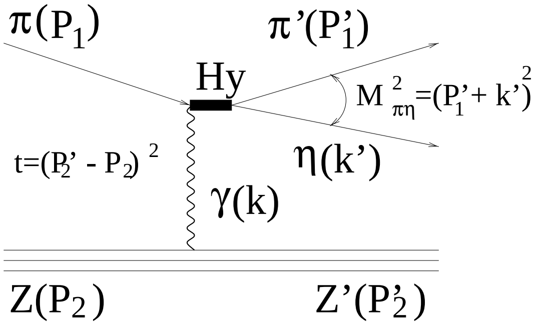

Figure 2: The Primakoff γ-pion Hybrid production process and kinematic variables (4-momenta): P1, P1$'$ = for initial/final pion, P2, P2$'$ = for initial/final target, k = for initial γ, k$'$ = for final η. By VDM, the exchanged γ behaves like a ρ.

If Pomeron exchange is indeed responsible for the production, then diffractive production in COMPASS can provide an additional handle with which to tackle the study of exotic waves.

One can succinctly summarize the situation as follows: a production of the wave $I^G(J^{PC}) = 1^-(1^{-+})$ is dependent on the strength of the $\pi\rho$ decay modes in the case of the Primakoff production. And both BNL and VES claim this decay mode for the different Hybrid candidates. For diffractive production, the relative strengths depend on the supposed decay modes $\pi_1(1400)\pi$ and $\pi_1(1600)\pi$ of the tensor glueball (2^{++}), since the Pomeron is thought to be on the Regge trajectory corresponding to the tensor glueball with a presumed mass around 2 GeV. Corresponding to the glueball decay $G(2^{++}) \to \pi^+ Hybrid$, one expects diffractive production via $\pi^- G(2^{++}) \to Hybrid$. This is an additional strong advantage of the COMPASS hybrid meson study. We can look forward to two complementary production modes of exotic mesons, increasing our chance for achieving a decisive advance on our understanding of the meson constituents. COMPASS can study Primakoff and diffractive production of non-strange light-quark hybrid mesons in the 1.4-2.5 GeV mass region, including all the hybrid candidates from previous studies.

2. Experimental Requirements

We considered [2, 3, 4, 5] the beam, target, detector, and trigger requirements for polarizability and hybrid meson studies, with minimum background contamination. Here we discuss briefly only the electromagnetic calorimeter and the Primakoff trigger.

The COMPASS Electromagnetic Calorimeter

COMPASS has a 2 meter diameter EM calorimeter, which is so far instrumented for the central 1 meter diameter. Funding for ADC readout electronics is still needed to be able to utilize the full 2 meter diameter coverage. As can be seen in Fig. 2, COMPASS needs to also detect ηs for the hybrid study. The two γs from η decay have half-opening angles $\theta^h_{\gamma\gamma}$ for the symmetric decays of $\theta^h_{\gamma\gamma} = m/E_\eta$, where m is the mass ($\eta$) and E$_\eta$ is the η energy. Opening angles are somewhat larger for asymmetric decays. In order to catch about 50% of the decays, it is necessary to subtend a cone with double that angle, i.e. $\pm 2m/E_\eta$, neglecting the angular spread of the original ηs around the beam direction. Consider an ECAL2 γ detector with a circular active area with 2 m diameter. Consider the $\pi\eta$ channel. For an ECAL2 of 1 m radius at 30 m from the target, ηs above E$_\eta$=33 GeV are therefore accepted. At half this energy, the acceptance practically vanishes. The acceptance of course depends on the Hybrid mass, mostly between 1.4 and 2.5 GeV for the planned COMPASS study. Detailed Monte Carlo

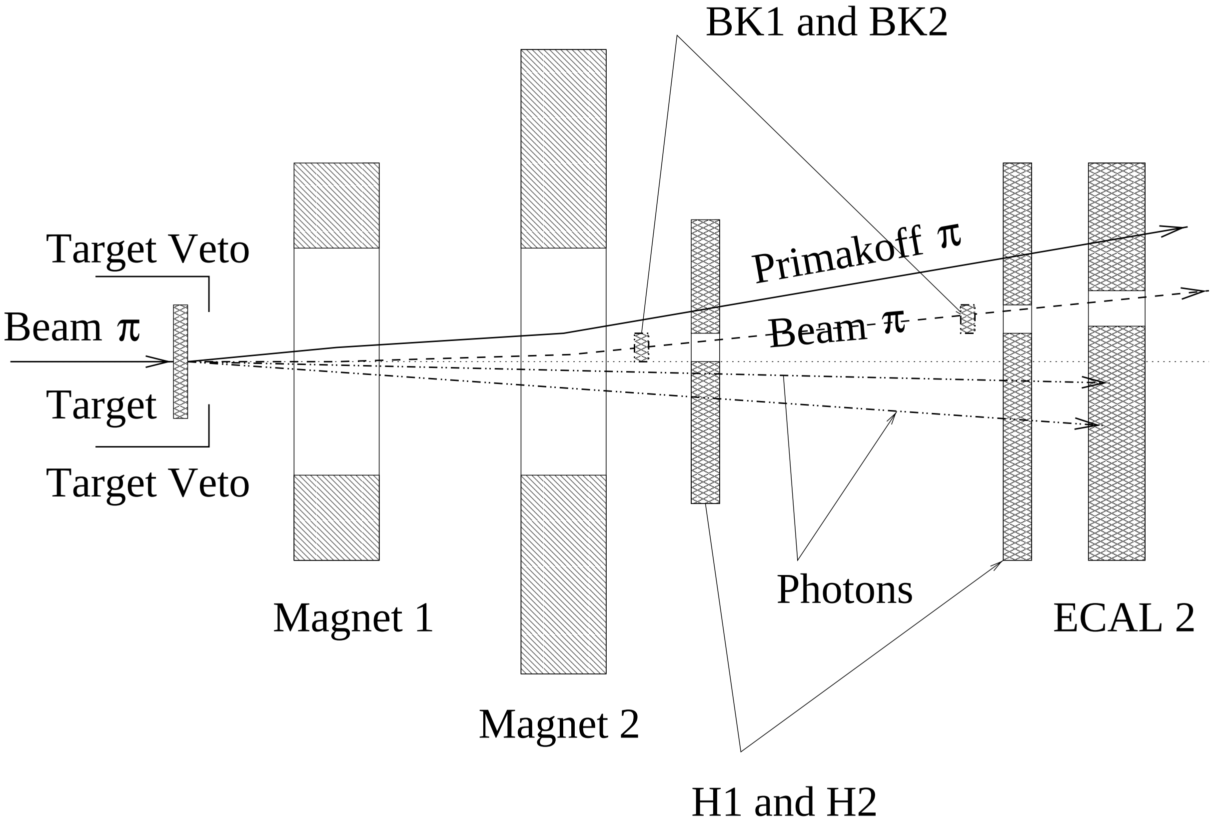

Figure 3: Detector layout for the COMPASS Primakoff Hybrid trigger. BK1,BK2=beam killer system, H1,H2=hodoscope system for charged particle detection, ECAL2=second photon calorimeter.

studies are in progress for the different possibly Hybrid decay modes, for a range of assumed masses. For the πf_1 channel, with for example $f_1 \rightarrow \pi\pi\eta$, the ηs will have low energy, and therefore large gamma angles. To maintain good acceptance for low energy ηs, the ECAL2 diameter should be 2 m or more.

The COMPASS Primakoff Trigger

We design [2, 3, 4, 5] the COMPASS Primakoff/Diffractive hybrid meson trigger to enhance the acceptance and statistics, and also to yield a trigger rate closer to the natural rate given by the Compton scattering and hybrid cross sections. We may veto target break-up events via veto scintillators around the target. For polarizability and hybrid meson physics, the trigger uses the characteristic decay pattern: one or three charged mesons with gamma hits, or three charged mesons and no gamma hits. The trigger [2, 3, 4, 5] for the $\pi\eta$ hybrid decay and polarizability channel (charged particle multiplicity =1) is based on a determination of the pion energy loss (via its characteristic angular deflection), correlated in downstream scintillator hodoscopes stations (H1 versus H2) with the aid of a fast matrix chip, as shown in Fig. 3. We also test alternative and/or complementary trigger concepts. For example, the non-interacting beam may be detected and vetoed by the Beam Kill veto trigger detectors BK1/BK2, which follow the pion trajectory, as shown in Fig. Fig. 3.

We studied [2, 3, 4] the acceptance for this trigger using the MC code POLARIS, which generates Primakoff pion-photon (polarizability) interactions, with realistic beam phase space. The simulation was done for beam momentum of 190 GeV/c. Using the beam killer system maintains good acceptance for Primakoff pions of momenta $<$ 160 GeV/c and photons of momenta $>$ 30 GeV/c. Introducing the lower threshold for the ECAL2 signal to be equal 20 GeV, helps to suppress background processes, but does not affect acceptance in its most efficient region. Finally, for the given trigger design, we achieve a large and flat acceptance versus photon Compton scattering angles [4]. This is important to extract reliably the pion polarizability by a fit of the data to the theoretical cross section. This trigger does not affect the acceptance at the important back-angles where the polarizability contribution is largest.

3. Objectives and Expected Significance

We studied the statistics attainable and uncertainties achievable for the pion polarizabilities in the COMPASS experiment, based on Monte Carlo simulations. We begin with an estimated 0.5 mb Compton scattering cross section per Pb nucleus and a total inelastic cross section per Pb nucleus of 0.8 barn. High statistics will allow systematic studies, with fits carried out for different regions of photon energy ω, Z^2, etc.; and polarizability determinations with statistical uncertainties of order 0.2. For the kaon polarizability, due to the lower beam intensity, the statistics will be roughly 50 times lower. A precision kaon polarizability measurement requires more data taking time.

For pion polarizability, in four months of running, we obtain 1.4×10^{13} beam pions. With a 1 % interaction length target, we obtain 1.4×10^{11} interactions. Based on the cross sections above, the Primakoff event rate R (events per interaction) is $R=6.3 \times 10^{-4}$. Therefore, in a 4 month run, one obtains 8.8×10^{7} Primakoff polarizability events at 100% efficiency. Considering efficiencies for tracking, γ detection, accelerator operation, trigger, we estimate a global efficiency of $\epsilon(\mathrm{total})=0.11$, or 9.6×10^{6} useful events per 4 month run. This is roughly a factor 1000 higher than the previous polarizability experiment.

We make rough estimates of the statistics attainable for hybrid production in the COMPASS experiment. Monte Carlo simulations in progress will refine these estimates. We assume a 125-1250μb Hybrid meson production cross section per Pb nucleus (near 1.5 GeV mass). This estimate is based on two considerations. First, a straightforward application of VDM with $\rho-\gamma$ coupling $g^2_{\rho\gamma}/\pi=2.5$, gives a width of $\Gamma(\pi_1 \rightarrow \pi\gamma)$ = 75-750 keV for a 1.5 GeV Hybrid, assuming $\Gamma(\pi_1 \rightarrow \pi\rho)$= 10-100 MeV, a range corresponding to 3.3-33% of the claimed 1.5 GeV hybrid width. Integrating the Primakoff Hybrid production differential cross section for a 280 GeV pion beam with this $\Gamma(\pi_1 \rightarrow \pi\gamma)$ width gives 125-1250 μb. Second, a FNAL E272 measurement indicated (but with high uncertainty) that $\Gamma(\pi_1 \rightarrow \pi\gamma) \times BR(\pi_1 \rightarrow \pi f_1) \approx 250$ keV for a 1.6 GeV Hybrid candidate. This would be consistent with the above maximum VDM $\Gamma(\pi_1 \rightarrow \pi\gamma)$ estimate for $\mathrm{BR}(\pi_1 \rightarrow \pi f_1)$ = 33%. With a total π inelastic cross section per Pb nucleus of 0.8 barn, the Primakoff Hybrid production event rate R (events per interaction) is then R= 1.6-16 $\times 10^{-4}$.

In four months of running, we obtain 1.4×10^{13} beam pions. With a 1% interaction length target, we obtain 1.4×10^{11} interactions. Therefore, one may obtain 2.2-22$\times 10^{7}$ Hybrid Primakoff events at 100% efficiency. We assume now a 50% accelerator operation efficiency. We also estimate a global 10% average detection efficiency over all decay channels for tracking, γ detection, η acceptance and identification, trigger acceptance, global geometric acceptance, and event reconstruction efficiency. All these effects give a global efficiency of 5%. Therefore, we may expect to observe a total of 1.1-11$\times 10^{6}$ Hybrid decays in all decay channels. For example, following the Close and Page predictions, we may expect 24% in πf_1, 2-8% in $\pi\rho$, 67% in $b_1\pi$, 0-4% in $\eta\pi$, 0-4% in $\eta'\pi$, etc.

For 2, 2.5, 3.0 GeV mass Hybrids, the number of useful events decreases by factors of 6, 25, and 100, respectively. But even in these cases, assuming again a global 5% efficiency, that represents very interesting potential samples of 1.8-18$\times 10^{5}$, 4.4-44$\times 10^{4}$, and 1.1-11$\times 10^{4}$ Hybrid meson detected events, with masses 2, 2.5, and 3 GeV respectively.

COMPASS can study hybrid meson candidates near 1.4, 1.6, 1.9 GeV produced by the Primakoff and Diffractive processes. COMPASS should also be sensitive to pionic hybrids in the 2-3 GeV mass range. We may obtain superior statistics for hybrid states if they exist, and via a different production mechanism, without possible complication by hadronic final state interactions. We may also get important data on the different decay modes for this state. The observation of these/other hybrids in different decay modes and in a different experiment would constitute the next important step following the evidence so far reported.

COMPASS provides a unique opportunity to investigate pion polarizabilities and QCD hybrid exotics. Taking into account the very high beam intensity, fast data acquisition, high acceptance and good resolution of the COMPASS setup, one can expect from COMPASS the highest statistics and a 'systematics-free' data sample that includes many tests to control possible systematic errors. Intercomparisons between COMPASS and past plus new experiments [12, 32, 33], with complementary methodologies, should allow fast progress on understanding pion polarizabilities and hybrid meson structure, and on fixing the systematic uncertainties.

4. Acknowledgments:

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1 PION AND KAON POLARIZABILITIES AT COMPASS

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The fundamental scientific questions addressed

The electric ($\bar{\alpha}$) and magnetic ($\bar{\beta}$) pion and Kaon polarizabilities characterize their deformation in an electromagnetic field, as occurs during $\gamma\pi$ or γ-Kaon Compton scattering. They depend on the rigidity of their internal structures as composite particles, and are therefore important quantities to test the validity of theoretical models. Pion (Kaon) polarizabilities can be studied at CERN COMPASS [1] via pion and Kaon Primakoff reaction such as $\pi^-\gamma \to \pi^{-\prime}\gamma$ Compton scattering [2, 3, 4]. In pion-photon Primakoff scattering, a high energy pion scatters from a virtual photon in the Coulomb field of the target nucleus. The pion polarizabilities are determined by their effect on the shape of the measured $\gamma\pi$ Compton scattering angular distribution. For theory, the χPT effective Lagrangian [9, 10], using data from radiative pion beta decay, predicts the pion electric and magnetic polarizabilities $\bar{\alpha}_\pi$ = -$\bar{\beta}_\pi$ = 2.7 ± 0.4, expressed in units of 10^{-43} cm^3. For the kaon, the χPT polarizability prediction [10] is $\bar{\alpha}_\pi = 0.5$. But available experimental pion polarizability results [6, 11] cover a large range of values and have large uncertainties. And Kaon polarizability measurements have never been carried out. New high precision pion and Kaon polarizability measurements will therefore provide important new tests of QCD chiral dynamics.

Major achievements since the last Long Range Plan

(1) For pion polarizabilities, a measurement is in progress [12] at MAMI-B at Mainz, via the $p(\gamma, n\pi^+\gamma')$ radiative pion photoproduction reaction. The $\gamma\pi^+$ Compton scattering cross section can be found by extrapolating such data to the pion pole, and thereby allows a measure of the pion polarizability. Theoretical studies were carried out [13] and will be continued, to minimize the errors associated with the extrapolation to the pion pole.

(2) The COMPASS experiment was approved by CERN. The Y2K setup run included a Primakoff test run with a 1 meter diameter EM calorimeter for the pion polarizability study. During the coming years of data taking, COMPASS run time will be shared between muon (gluon polarization) and pion beam physics programs. During muon runs, setup and normalization of the pion polarizability program may proceed via measurements of muon-photon Primakoff scattering.

(3) A pion polarizability experiment with polarized tagged photons has been proposed [14] for the JLAB 12 GeV upgrade.

Short and Long term (<3 yrs and long term <10 yrs) U.S. outlook

For the long term, JLab may run and analyze its pion polarizability experiment.

Comparison of U.S. and global effort

The U.S. and global efforts contine strongly on the experimental and theoretical fronts for pion polarizabilities. The aim is to achieve consistent results in different experiments. Only then will it be possible to unambiguously establish definitive values for pion polarizabilities. COMPASS plans to use a 200 GeV pion beam and a photon target, and magnetic spectrometers and electromagnetic calorimeters, to measure pion-photon Compton scattering, and the pion polarizability. Primakoff scattering has the advantages also that meson exchange backgrounds and final state interactions are strongly suppressed.

For the short term, analysis of the Mainz MAMI-B data run, scheduled for completion Jan. 2001, should lead to a new pion polarizability result. Also, the COMPASS experiment begins its muon and pion beam physics programs in 2001. Associated Monte Carlo simulations are in progress. For the long term, COMPASS, JLab, and Mainz (MAMI-C A2 collaboration at higher tagged photon energies) may run and analyze and compare data from different experiments for pion polarizabilities. Only COMPASS may measure Kaon polarizabilities. Such data and intercomparisons will be valuable for fixing the systematic uncertainties in pion and Kaon polarizability measurements.

Other issues

For the kaon polarizability program, a modest COMPASS upgrade will be required to achieve pion/Kaon beam particle identification. One may achieve a tagged Kaon beam intensity of order 1 MHz, by a photomultiplier detector upgrade (to allow high beam intensities) of the exisiting COMPASS CEDARS Cerenkov detectors.

2 HYBRID MESON STRUCTURE AT COMPASS

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The fundamental scientific questions addressed

To understand confinement, it is of major importance and relevance to establish the existence of hybrid mesons and to study their structure. The hybrid ($q\bar{q}g$) mesons contain explicit glue as opposed to hidden glue in conventional hadrons. Understanding explicit glue is critical, considering that most of the mass around us is made of gluons. COMPASS [1] may study Primakoff and diffractive production of non-strange light-quark hybrid mesons in the 1.4-3.0 GeV mass region, including hybrid candidates from previous studies [4, 5].

Major achievements since the last Long Range Plan

(1) From the experimental efforts at BNL, IHEP, KEK, CERN, a number of $J^{PC} = 1^{-+}$ resonant signals were reported [24, 25, 26, 27, 28, 29, 30, 31] at masses between 1.4 and 1.9 GeV in a variety of decay channels, including the $\rho\pi$ channel. Confidence in hybrid mesons is increasing, but further complementary evidence is still sorely needed.

(2) Theoretical studies of hybrid mesons are shedding new light on their structure. As examples, Barnes and Isgur [18, 19] via the flux-tube model, recently calculated the mass of the lightest gluonic hybrid to be around 1.9 GeV, with the quantum numbers of $J^{PC} = 1^{-+}$; while Close and Page [20] predict the decay modes of such a gluonic hybrid.

(3) The COMPASS experiment was approved by CERN. It already had an equipment setup run in summer 2000, including a test run with a 1 meter diameter EM calorimeter. During the coming years of data taking, run time will be shared between muon and pion beam physics programs. Besides the Primakoff program, COMPASS runs will involve studies of gluon polarization in the proton, using the muon beam to study photon-gluon fusion.

(4) GSI Darmstadt [32] plans a hybrid meson program via a new facility for $p\bar{p}$ reactions.

(5) The planned 12 GeV JLab upgrade would allow hybrid meson studies at JLab Hall D [15, 16, 17].

(6) Analysis of CERN LEP data [33] may reveal two-photon production of exotic mesons. From the vector-dominance model, it is clear that two-photon systems should be rich in 4-quark exotics. Similarly, the Fermilab CDF (no Roman pots) and D0 (Roman pots being built) can give double-Pomeron production of exotic mesons [33]. Pomerons are gluonic; the mesons produced could be rich in gluonic hybrids.

Short and long term (<3 yrs and long term <10 yrs) U.S. outlook

Further BNL data (from analysis of completed experiments) and further theoretical calculations are becoming available. For the long term, JLab plans to take and analyze data for hybrid meson structure.

Comparison of U.S. and global effort

The U.S. and global efforts contine strongly on the experimental and theoretical fronts for hybrid meson studies. Evidence from completely different experiments are needed to prove conclusively that the previous hybrid meson evidence is not the result of some incorrectly interpreted artifice.

COMPASS uses a 200 GeV pion beam and photon/Pomeron targets, and magnetic spectrometers and EM calorimeters, to measure completely pion-photon and pion-Pomeron reactions. In Primakoff scattering, a high energy pion scatters from a virtual photon in the Coulomb field of the target nucleus; while for Diffractive scattering, the pion scatters from an exchanged Pomeron. The relevant Primakoff and Diffractive reactions are:
$\pi^-\gamma \ or \ \pi^-Pomeron \rightarrow Hybrid \rightarrow \rho\pi, \eta\pi, \eta'\pi, b_1(1235)\pi, \pi f_1$, etc.
Consider some typical experimental angular distributions, such as those for the $\pi^-\gamma \rightarrow \eta\pi$ for different values of the $\eta\pi$ invariant mass. If these events are associated with the production and decay of a $J^{PC} = 1^{-+}$ hybrid state, which are quantum numbers not possible for a regular $q\bar{q}$ meson, then a detailed partial wave analysis (PWA) of a large data sample of

such $\eta\pi$ events (centered at a given mass, with a given width, and with appropriate resonance phase motion) would require these quantum numbers. In COMPASS, the relative strengths of hybrid compared to other close lying states, may improve significantly compared to previous production experiments. This may diminish the PWA uncertainties that affected previous hybrid production experiments [5].

For Primakoff scattering, the hybrid meson production cross section depends on the strength of its $\pi\rho$ coupling, since the virtual photon target behaves like a ρ by vector dominance model. For diffractive production, the relative strengths depend on the decay modes of the tensor glueball (2^{++}), since the Pomeron is thought to be on the Regge trajectory corresponding to the tensor glueball with a presumed mass around 2 GeV. Corresponding to the glueball decay $G(2^{++}) \to \pi^+ Hybrid$, one expects diffractive production via $\pi^- G(2^{++}) \to Hybrid$. This is an additional advantage of the COMPASS hybrid meson study [5]. COMPASS can look forward to two complementary hybrid production modes, increasing our chance for achieving a decisive advance on our understanding of the meson constituents. Furthermore, in Primakoff (photon exchange) and diffractive (glue-rich pomeron exchange) hybrid production, meson exchange backgrounds are strongly suppressed, which is an important advantage compared to previous Hybrid production experiments.

For the short term, the COMPASS experiment should be in production for the muon physics program, including setup of initial Primakoff physics programs. Monte Carlo simulations for the hybrid studies can be completed. Further VES and CB data (from analysis of past experiments) and theoretical calculations will become available. For the long term, COMPASS and GSI and JLab may run and analyze and compare data for hybrid meson structure.

Other issues

COMPASS has a 2 meter diameter EM ECAL2 calorimeter, which is so far instrumented with ADC readout for the central 1 meter diameter, appropriate to pion polarizability studies. For the hybrid meson program, a modest COMPASS upgrade will be required to achieve ADC readout electronics (via individual or multiplexing readout) for the full 2 meter diameter calorimeter coverage. This would allow detection of ηs from hybrid decay (η or πf_1 followed by $f_1 \to \pi\pi\eta$, etc.) with high and flat acceptance.