Submitted to the Proceedings,
XXXVII International Winter Meeting on Nuclear Physics
Bormio, Italy, Tel Aviv U. Preprint TAUP-2562-99, Jan. 1999.

Hadron-Photon Interactions in COMPASS

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Abstract:

The CERN COMPASS experiment will investigate hadron-photon interactions, to achieve a unique Primakoff Coulomb physics program based on hadron polarizability, hybrid mesons, chiral anomaly, and meson radiative transition studies. In COMPASS, pion (kaon) polarizabilities and radiative transitions will be measured via dedicated Primakoff effect reactions such as $\pi^-\gamma \to \pi^{-\prime}\gamma$ and $\pi^-\gamma \to M$ (meson). We will also study pionic and kaonic hybrid mesons in COMPASS by Primakoff production. We will also study the radiative transition of a pion to a low mass two-pion system, $\pi^-\gamma \to \pi^{-\prime}\pi^0$, for a measure of the chiral anomaly amplitude $F_{3\pi}$ (characterizing $\gamma \to 3\pi$). Our objectives are to determine new properties of hadrons and to provide important new tests of QCD chiral dynamics.

The CERN COMPASS experiment use 50-280 GeV beams (μ, π, K, p) and a virtual photon target, and magnetic spectrometers and calorimeters to measure the complete kinematics of hadron-photon reactions. The COMPASS experiment is currently under construction, and scheduled in 2000 to begin data runs, with muons initially and hadrons following. The Primakoff program in COMPASS is approved as the first hadron physics program. We carry out simulation studies to optimize the beam, detector, trigger, and hardware/software for achieving high statistics data with low systematic uncertainties in this program. For kaon studies, our results will be the first ever. For pion studies, we will improve previous results by more than two orders of magnitude. We will implement special detectors and triggers for hadron-photon reactions. We will prepare the COMPASS hadron-photon Primakoff studies by setting up with muon-photon Primakoff tests.

1. Hadron-Photon Interactions:

The COMPASS physics programs [1, 2] include studies of hadron-photon Primakoff interactions using 50-280 GeV/c negative beams (pions, kaons) and positive beams (pions, kaons, protons) together with a virtual photon target in dedicated data runs. Pion and kaon and proton polarizabilities, hybrid mesons, the chiral anomaly, and radiative transitions can be studied in this way, and can provide significant tests of QCD and chiral perturbation theory (χPT) predictions. Preliminary COMPASS Primakoff planning studies appear in detail in the proceedings of the 1997 Mainz Chiral Dynamics workshop and Prague COMPASS summer school [3, 4]. The objectives and significance of the studies are further described below.

Pion Polarizabilities

For the pion polarizability, $\gamma\pi$ scattering was measured (with large uncertainties) with 40 GeV pions [5] via radiative pion scattering (pion Bremsstrahlung) in the nuclear Coulomb field:

$$\pi + Z \to \pi' + \gamma + Z'. \tag{1}$$

In this measurement, the incident pion Compton scatters from a virtual photon in the Coulomb field of a nucleus of atomic number Z; and the final state γ and pion are detected in coincidence. The radiative pion scattering reaction is equivalent to $\gamma + \pi^- \to \gamma + \pi^-$ 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 [6, 7] that relates processes involving real photon interactions to production cross sections involving the exchange of virtual photons.

In the 40 GeV radiative pion scattering experiments, it was shown experimentally [5] and theoretically [8] that the Coulomb amplitude clearly dominates, and yields sharp peaks in t-distributions at very small squared four momentum transfers (t) to the target nucleus t $\leq 6 \times 10^{-4}$ (GeV/c)^2. Backgrounds from strong processes were low. The backgrounds are expected to be lower at the higher energies planned for the CERN COMPASS experiment.

For the $\gamma\pi$ interaction at low energy, χPT provides a rigorous way to make predictions via a Chiral Lagrangian written in terms of renormalized coupling constants L_i^r [9]. With a perturbative expansion of the effective Lagrangian, the method establishes relationships between different processes in terms of the L_i^r. For example, the radiative pion beta decay and electric pion polarizability are expressed as [10]:

$$F_A/F_V = 32\pi^2(L_9^r + L_{10}^r);\ \bar{\alpha}_\pi = \frac{4\alpha_f}{m_\pi f_\pi^2}(L_9^r + L_{10}^r); \tag{2}$$

where f_π is the pion decay constant, m_π is the pion mass, F_A and F_V are the axial vector and vector coupling constants in the decay, and α_f is the fine structure constant. The experimental ratio $F_A/F_V = 0.45 \pm 0.06$, leads to $\bar{\alpha}_\pi = -\bar{\beta}_\pi = 2.7 \pm 0.4$, where the error shown is due to the uncertainty in the F_A/F_V measurement [10, 11]. All polarizabilities are expressed in Gaussian units of 10^{-43} cm^3. The χPT prediction [10] for the pion polarizability is $\bar{\alpha}_\pi = 2.7$. Ref. [10] showed that meson exchange via a pole diagram involving the $a_1(1260)$ resonance provides the main contribution ($\bar{\alpha}_\pi = 2.6$) to the polarizability. Ref. [12] assuming a_1 dominance finds $\bar{\alpha}_\pi = 1.8$. For the kaon, the χPT polarizability prediction [10] is $\bar{\alpha}_K = 0.5$. A more extensive theoretical study of kaon polarizabilities was given recently [13].

The pion polarizabilities deduced by Antipov et al. [5] 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 have large uncertainties. There is a clear need for new and improved radiative pion scattering data.** The pion polarizabilty provides an important test of chiral dynamics.

Hybrid Mesons

The hybrid ($q\bar{q}g$) mesons, along with glueballs (gg) are one of the most amazing consequences of the non-abelian nature of QCD. Detection of these exotic states is a long-standing experimental puzzle. The most popular approach for the hybrids search is to look for the "oddballs" - mesons with the quantum numbers not allowed for the ordinary $q\bar{q}$ states, for example $J^{PC} = 1^{-+}$, decaying to $\eta\pi$, $\eta'\pi$, $f_1(1285)\pi$, $b_1(1235)\pi$, etc.

From more than a decade of experimental efforts at IHEP [14, 15, 16], CERN [17], KEK [18] and BNL [19], several hybrid candidates have been identified. The most recent information came from BNL E852 experiment [19] which studied the $\pi^- p$ interaction at 18 GeV/c. They reported $J^{PC} = 1^{-+}$ resonant signals in $\eta\pi^-$ and $\eta\pi^0$ systems as well as in $\pi^+\pi^-\pi^-$, $\pi^-\pi^0\pi^0$, $\eta'\pi^-$ and $f_1(1285)\pi^-$. At the same time, a VES group [16] has published analysis of $\eta\pi^-$, $\eta'\pi^-$, $f_1(1285)\pi^-$, $b_1(1235)\pi^-$ and $\rho\pi^-$ systems production in $\pi^- Be$ interaction at 37 GeV/c. Although the $J^{PC} = 1^{-+}$ wave is clearly seen by VES in all channels, there is no indication for the presence of a narrow ($\Gamma \sim 0.2\ GeV$) resonance in any of them. But an observed abnormally high ratio of $\eta'\pi$ to $\eta\pi$ P-wave is considered as evidence for the hybrid nature of this exotic wave.

It should be mentioned that the partial wave analysis (PWA) of systems such as $\eta\pi$ or $\eta'\pi$ in the mass region below 2 GeV is particularly difficult. This is so because (1) this region is dominated by the strong 2^+ "background" (a1 resonance), and (2) that the PWA may give ambiguous results [15] for the weaker 1^{-+} wave. The problem is that the PWA of the $\eta\pi$ system must take into account S, P and D waves, and the number of observables is not sufficient to solve unambiguously all equations. Looking at the partial wave solutions as a function of mass, each partial wave can have as many as eight different curves to describe its strength and phase, as discussed in ref. [15]. It is therefore extremely important to have extra information from different hybrid production mechanisms where the physics is different and such ambiguities may look different. Only by comparing results of different experiments in this way, can we establish unambiguously the existence or non-existence of hybrid (or exotic) meson states. COMPASS will look for Primakoff production of pionic and kaonic hybrid mesons in the 1-2 GeV mass region, including all hybrid candidates from previous studies.

Chiral Axial Anomaly

The Chiral Axial Anomaly can also be studied with 50-280 GeV pion beams. For the γ-π interaction, the $O(p^4)$ chiral lagrangian [9, 20] includes Wess-Zumino-Witten (WZW) terms [21, 22], which lead to a chiral anomaly term [21, 22, 23] in the divergence equations of the currents. This leads directly to interesting predictions [22] for the processes $\pi^0 \to 2\gamma$ and $\gamma \to 3\pi$; and other processes as well [22]. The two processes listed are described by the amplitudes F_π and $F_{3\pi}$, respectively.

The chiral anomaly term leads to a prediction for F_π and $F_{3\pi}$ in terms of N_c, the number of colors in QCD; and f_π, the charged pion decay constant. The $O(p^4)$ F_π prediction for $\pi^0 \to 2\gamma$ is in agreement with experiment [22]. The $F_{3\pi}$ prediction is [24, 25]:

$$F_{3\pi} = \frac{N_c(4\pi\alpha)^{\frac{1}{2}}}{12\pi^2 f_\pi^3} \sim 9.7 \pm 0.2\ GeV^{-3},\ O(p^4). \tag{3}$$

The experimental confirmation of this equation would demonstrate that the $O(p^4)$ terms are sufficient to describe $F_{3\pi}$.

The amplitude $F_{3\pi}$ was measured by Antipov et al. [23] at Serpukhov with 40 GeV pions. Their study involved pion production by a pion in the nuclear Coulomb field via the Primakoff reaction:

$$\pi^- + Z \to \pi^{-\prime} + \pi^0 + Z'. \tag{4}$$

In the one-photon exchange domain, eq. 4 is equivalent to:

$$\pi^- + \gamma \to \pi^{-\prime} + \pi^0, \tag{5}$$

and the 4-momentum of the virtual photon is k = P_Z-$P_{Z'}$. The cross section formula for the Primakoff reaction depends on $F_{3\pi}^2$. The Antipov et al. data sample (roughly 200 events) covering the ranges $-t < 2. \times 10^{-3} (GeV/c)^2$ and $s(\pi^-\pi^0) < 10.\ m_\pi^2$. The small t-range selects events predominantly associated with the exchange of a virtual photon, for which the target nucleus acts as a spectator. Diffractive production of the two-pion final state is blocked by G-parity conservation. The experiment [23] yielded $F_{3\pi} = 12.9 \pm 0.9(stat) \pm 0.5(sys)\ GeV^{-3}$. This result differs from the O(p^4) expectation by at least two standard deviations; so that the chiral anomaly prediction at O(p^4) is not confirmed by the available $\gamma \to 3\pi$ data.

Bijnens et al. [22] studied higher order χPT corrections in the abnormal intrinsic parity (anomalous) sector. They included one-loop diagrams involving one vertex from the WZW term, and tree diagrams from the O(p^6) lagrangian. They determine parameters of the lagrangian via vector meson dominance (VMD) calculations. The higher order corrections are small for F_π. For $F_{3\pi}$, they increase the lowest order value from 7% to 12%. The one-loop and O(p^6) corrections to $F_{3\pi}$ are comparable in strength. The loop corrections to $F_{3\pi}$ are not constant over the whole phase space, due to dependences on the momenta of the 3 pions. The average effect is roughly 10%, which then increases the theoretical prediction by 1 GeV^{-3}. The prediction is then $F_{3\pi} \sim 10.7$, closer to the data. The limited accuracy of the existing data, together with the new calculations of Bijnens et al., motivate an improved and more precise experiment. The expected number of near threshold two-pion events in COMPASS is several orders of magnitude larger than in all previous experiments [24].

Radiative Transitions

Radiative decay widths of mesons and baryons are powerful tools for understanding the structure of elementary particles and for constructing dynamical theories of hadronic systems. Straightforward predictions for radiative widths make possible the direct comparison of experimental data and theory. The small value of branching ratios of radiative decays makes them difficult to measure directly, because of the large background from strong decays. Studying the inverse reaction $\gamma + \pi^- \to M^-$ provides a relatively clean method for the determination of the radiative widths. Very good tracking resolution is needed and available in COMPASS to measure initial and final state momenta, and to thus exhibit the Primakoff signal at small four momentum transfer t, where the electromagnetic processes dominate over the strong interaction.

We will study via COMPASS radiative transitions of incident mesons to higher excited states. We will obtain new data [4] for radiative transitions leading from the pion to the ρ, $a_1(1260)$, and $a_2(1320)$; and for the kaon to K* and higher resonances. Independent and higher precision data for these and higher resonances will be valuable in order to allow a more meaningful comparison with theoretical predictions. For example, the $\rho \to \pi\gamma$ width measurements [6] range from 60 to 81 keV; the $a_1(1260) \to \pi\gamma$ width measurement [26] is 0.64 ± 0.25 MeV; the $a_2(1320) \to \pi\gamma$ width [27] is $\Gamma = 0.30 \pm\ 0.06$ MeV. For $K^* \to K\gamma$, the widths obtained previously [28, 29] ranged from 48-51 keV with errors 5-11 keV.

The COMPASS Primakoff Trigger

For all the Primakoff physics topics discussed above, due to the small scattering angles, a trigger based on downstream information is desired. The trigger should use the characteristic

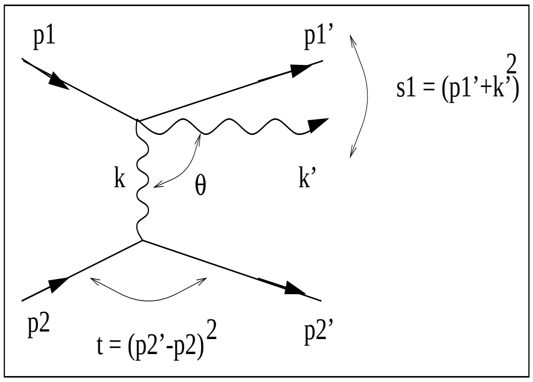

Figure 1: The Primakoff γ-hadron Compton process and kinematic variables (4-momenta): p1, p1$'$ = for initial/final hadron, p2, p2$'$ = for initial/final target, k, k$'$ = for initial/final gamma, and θ the scattering angle of the γ in the alab frame.

pattern of a gently deflected hadron and one or two photon hits in the EM calorimeter close to the neutral beam direction. We design the COMPASS Primakoff trigger in this way, which enhances the acceptance and statistics, and also yields a trigger rate closer to the natural rate given by the low Primakoff cross section. We develop the trigger scheme with the help of simplified MC generators, as follows: a solution based on fast scintillator hodoscopes that follow the hadron trajectory, and energy deposit signals from photon calorimeters.

For COMPASS we forsee a three-level Primakoff trigger scheme: T0 = beam definition, T1 = event topology, T2 = online software filter. T0 is a fast logical relation between 1 mip (minimum ionizing particle) signals from thin transmission and veto (hole) scintillators before the target, and from the upstream CEDARS Cherenkov counters providing beam PID. T1 is a downstream coincidence between scintillation hodoscope signals from the pion track and total energy deposit signal in the photon calorimeter. T2 is an intelligent software filter, placed in the DAQ stream after the event builder, which counts the number of reconstructed segments downstream from the target, and also sets cuts on event quality characteristics. Triggers for different Primakoff topics may have different logic, but all will run in parallel.

As an example, pion 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 trigger design should suppress the beam rate by at least a factor 10^4, achieving high acceptance efficiency for Primakoff scattering events. 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 accompaning 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 offline using the beam and vertex silicon detectors.

The T1 trigger scheme (for photon-hadron reactions with one charged hadron and one or more photons in the final state) is shown in Fig. 2. BK1 and BK2 are assumed to be small scintillator hodoscopes with moderate segmentation (~1cm) in the beam bend plane. An anticoincidence on certain regions of the BK1/BK2 correlation will serve to veto non-interacting beam pions. According to Monte Carlo simulation, this achieves beam suppression (190 GeV/c) with 99.8% efficiency, while maintaining 100% efficiency for all Primakoff scattered pions with momenta lower than 160 GeV/c. The BK1 hodoscope size should be optimized to accept both Primakoff and beam pions. The H1 hodoscope vetos charged particles with larger angles, and also events with higher multiplicity. The H2 and H3 hodoscopes could serve to veto non-Primakoff events and to also trigger on Primakoff scattered pions. This is achieved by measuring the pion energy loss via characteristic angular deflection correlations in these

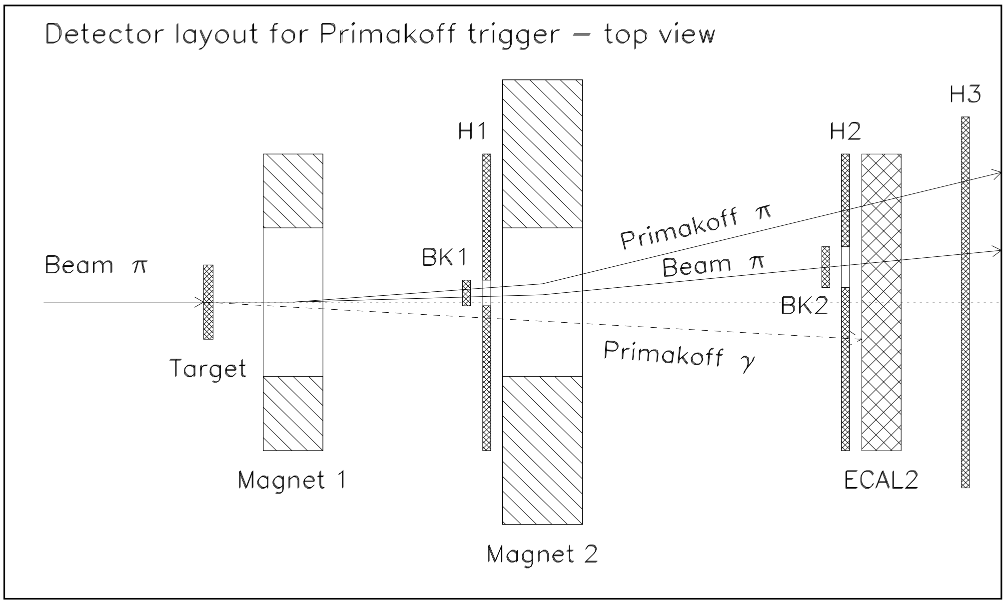

Figure 2: Detector layout for the COMPASS Primakoff trigger. BK1,BK2=beam killer system, H1,H2,H3=hodoscope system for charged particle vetoing and Primakoff pion detection, ECAL2=second photon calorimeter.

hodoscopes. A fast matrix chip is needed for this purpose, as developed for the standard muon energy loss trigger in planned COMPASS studies of gluon polarization in the proton. In principle, a coincidence based on BK1/BK2 segmentated hodoscope correlations, accepting correlation zones differing from the beam topology, could be also used to trigger on the Primakoff scattered pion.

That trigger configuration strongly suppresses (with minimal acceptance loss) backgrounds associated with both non-interacting beam particles and those involving nuclear interation of pions in the target and in COMPASS apparatus material. Finally, a decision signal for Primakoff pion detection, based on the hodoscope correlations, is required to be in coincidence with a decision signal for a minimum total energy produced by a Primakoff gamma-ray in the electromagnetic calorimeter ECAL2. The threshold for the ECAL2 signal needs to be optimized in order to affect only the kinematic region of the highest energy Primakoff pions, whose detection efficiency is already significantly reduced by the BK1/BK2 beam killer.

We studied the acceptance for this trigger using our MC code POLARIS, which generates Primakoff pion-photon (polarizability) interactions, with realistic beam phase space. In Fig. 3 we plot the acceptance for the Primakoff pion and photon momenta distributions in the lab system, and for photon Compton scattering angle in the projectile (alab) frame. 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 (see Fig. 3a,b). 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 (see Fig. 3c). Finally, for the given trigger design, we achieve a large and flat

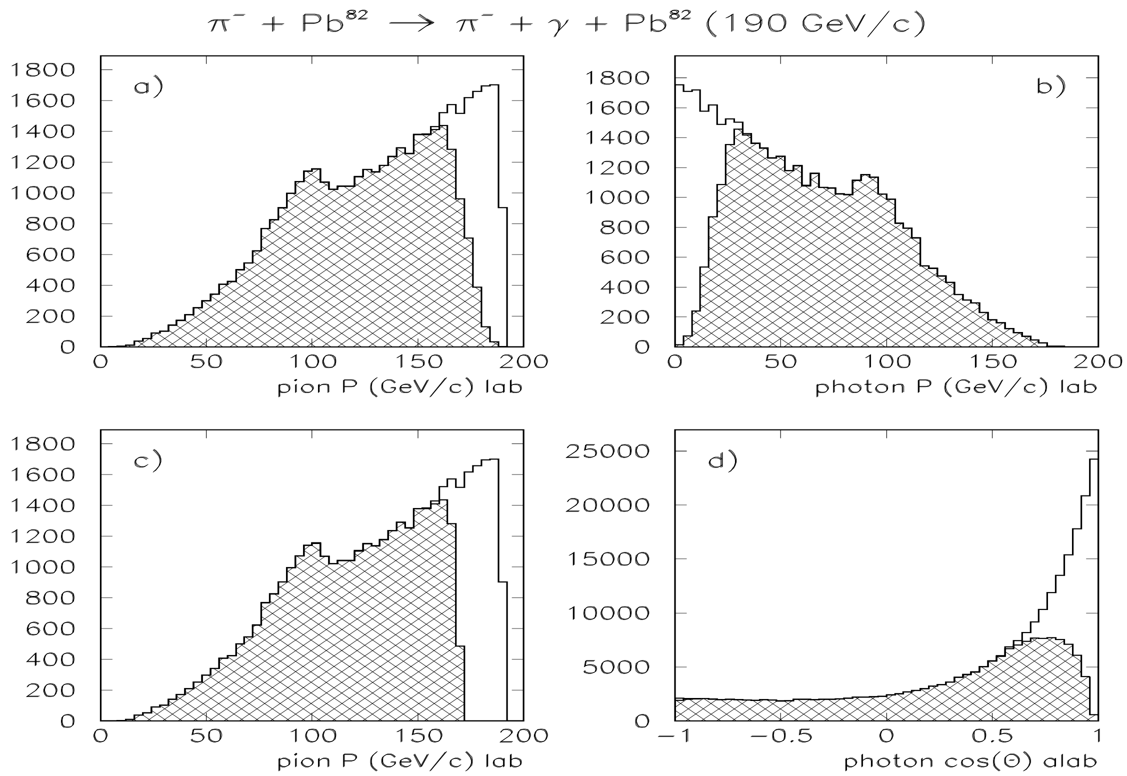

Figure 3: MC simulation of the pion polarizability measurement in the COMPASS 190 GeV/c beam: (a), (b) - Effect of beam killer system on the acceptance of the Primakoff pion and photon momentum distributions; (c) - Effect on Primakoff pion momenta distribution of beam killer system together with ECAL2 set at 20 GeV lower threshold; (d) - Acceptance for $\gamma\pi \to \gamma\pi$ angular distribution versus $\cos(\theta)$, with θ the γ scattering angle in the alab frame. The hatched areas of the histograms correspond to kinematic regions accepted by the trigger.

acceptance versus photon Compton scattering angles (see Fig. 3d). 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.

2. Plan of Operation:

The CERN COMPASS experiment uses 50-280 GeV beams (μ, π, K, p) and a virtual photon target, and magnetic spectrometers and calorimeters to measure the complete kinematics of hadron-photon reactions. The COMPASS experiment is currently under construction, and scheduled in 2000 to begin data runs, with muons initially and hadrons following. The Primakoff program in COMPASS is approved as the first hadron physics program. The Primakoff physics program in COMPASS will benefit from high statistics, excellent beam focussing and momentum analysis, and dedicated runs.

We need to achieve high statistics data with low systematic uncertainties in this program. Accurate simulations are required using the new C-programmed COMPASS COMGEANT package, presently being developped, containing the updated experimental setup, trigger and the DAQ schemes, accurate magnetic field mapping, and event reconstuction. We work on this package and incorporate our Primakoff generators, including Hybrid Meson and Chiral Anomaly generators. We develop COMPASS event reconstruction algorithms, and test them on COMGEANT simulated events.

For the COMPASS Primakoff physics effort, we need to plan, construct, and implement all hardware and software for all triggers of interest for this physics. We prepare the COMPASS hadron-photon Primakoff trigger system by the following phases: (1) further investigate trigger schemes, such as the hodoscope matrix energy loss trigger discussed above, (2) refine our MC trigger simulations using COMGEANT, (3) construct the trigger hardware, including an upgrade of the existing CEDARS Cherenkov beam PID detector, scintillation hodoscopes, fast signal summing circuitry, mechanical supports, etc., (4) installation of the system at CERN, (5) setting up the trigger detectors and electronics in the COMPASS muon beam, (6) taking preliminary data with muons, writing event reconstruction algorithms, and checking trigger performance, (7) use it for running the COMPASS experiment with hadron beam.

3. Objectives and Expected Significance:

The experimental pion polarizability determination to date has large uncertainties. Kaon polarizabilities have never been measured. We will determine the $\gamma\pi$, γK, and γp Compton cross sections, and associated polarizabilities, and also the $\gamma\mu$ Compton scattering cross section as a check. For kaon studies, COMPASS results will be the first ever. For pion studies, we will improve previous results by more than two orders of magnitude, as we discuss below. The proton studies will provide a check on our methodology, since the proton polarizability has been measured previously by standard γp scattering.

We studied the statistics attainable and uncertainties achievable for the pion polarizabilities in the COMPASS experiment, based on Monte Carlo simulations. We estimated 80 events/spill from the pion Primakoff effect, corresponding to 10^7 events per month at 100% efficiency. We assume a trigger efficiency of 75%, an accelerator operating efficiency of 50%, and a tracking efficiency of 80%. One may then expect to observe as many as 3×10^6 Primakoff Compton events per month of operation, following setup of COMPASS. Statistics of this order 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, and should be carried out following the analysis of the initial lower statistics data runs.

Comparing chiral anomaly to polarizability data, we expect roughly 300 times lower statistics, due to the 140 times lower cross section and the lower π^0 detection efficiency [24].

COMPASS can contribute significantly to the further investigation of hybrids by studying Primakoff production of $J^{PC} = 1^{-+}$ $\tilde{\rho}$ hybrids. The possibilities for Primakoff production of the $\tilde{\rho}$ with energetic pion beams, and detection via different decay channels has been discussed by Zielinski et al. [30], and Monte Carlo simulations for this physics were also carried out for COMPASS [31]. Considering vector dominance models, if the $\tilde{\rho}$ has a 1-10 MeV branching width into the $\pi\rho$ channel, a branching width of $\tilde{\rho}$ into the $\pi\gamma$ channel should be 3-30 keV [30]. A hybrid state with such a large radiative width would be produced at detectable levels through the Primakoff mechanism in COMPASS. The COMPASS trigger should allow observation of the $\tilde{\rho}$ via the $\eta\pi^-$ decay mode. With a relative P wave (L=1), the $\eta\pi^-$ system has $J^{PC} = 1^{-+}$. The other decay channels of $\tilde{\rho}$ may be studied simultaneously in COMPASS by relatively simple particle multiplicity triggers (three charged particles in final state, etc.).

The evidence presented for the hybrid (pionic) meson offers COMPASS an exceptional opportunity to take the next steps in this exciting field. COMPASS can study hybrid meson candidates near 1.4 GeV produced by the Primakoff process. COMPASS should also be sensitive to pionic hybrids at higher excitation, and also to kaonic hybrids, which have not yet been reported. We may obtain superior statistics for a hybrid state if it exists, 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 this hybrid in different decay modes and in a different experiment would constitute the next important step following the evidence so far reported.

COMPASS can provide a unique opportunity to investigate QCD exotics, glueballs and hybrids, produced via different production mechanisms: central production for glueballs (not the subject of this proposal) and Primakoff production for hybrids. 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. The COMPASS effort should significantly improve our understanding of hybrid physics.

4. Acknowledgements:

The Tel Aviv U. group acknowledges support by the U.S.-Israel Binational Science Foundation (BSF) and the Israel Science Foundation founded by the Israel Academy of Sciences and Humanities. Thanks are due to B. Povh and J. Pochodzalla of MPI Heidelberg (Kernphysik), for their hospitality and interesting discussions during the preparation of this paper. Thanks are due also to our COMPASS collaborators for continued interest: B. Barnett, F. Bradamante, A. Bravar, S. U. Chung, M. Faessler, O. Gavrishuk, M. Lamanna, J. Lichtenstadt, A. Olshevski, S. Paul, I. Savin, L. Schmitt, H.-W. Siebert, A. Singovsky, V. Sougonyaev, G. Mallot, V. Poliakov, D. von Harrach, Th. Walcher, U. Wiedner.

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