Plans for a measurement of pion polarizabilities at COMPASS.

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The pion electromagnetic structure can be probed in $\pi^- + (A,Z) \to \pi^- + (A,Z) + \gamma$ Compton scattering in inverse kinematics (Primakoff reaction) and described by the electric (α_π) and the magnetic (β_π) polarizabilities that depend on the rigidity of pion's internal structure as a composite particle. Values for pion polarizabilities can be extracted from the comparison of the differential cross section for scattering of point-like pions with the measured cross section. The opportunity to measure pion polarizability via the Primakoff reaction at the COMPASS experiment was studied with a π^- beam of 190 GeV. The obtained results are used for preparation of the new measurement.

1. Introduction

In classical physics the polarizability of a medium or a composite system is a well known characteristics related to the response of the system to the presence of an external electromagnetic field. This concept can be extended to the case of composite particles like the pion. In the case of the pion, the electric (α_π) and magnetic (β_π) polarizabilities characterize the response of the quark substructure to the presence of an external electromagnetic field in the $\pi\gamma$ Compton-like scattering. These parameters are fundamental ones for any theory describing the pion structure.

Different models like chiral perturbation theory, dispersion sum rules, QCD sum rule, NJL model and quark confinement model (see [1]-[5]) predict that the $\alpha_\pi + \beta_\pi$ is close to zero while the values for $\alpha_\pi - \beta_\pi$ are in a range $(6-14) \times 10^{-4}\ fm^3$.

Several attempts to measure these quantities were done (see [6]-[15]). But the obtained results are affected by large uncertainties and cannot be used for tests of theoretical predictions. New more precise measurements are needed.

2. Primakoff reaction studies at COMPASS

The Primakoff reaction

$$\pi^- + (A,Z) \to \pi^- + (A,Z) + \gamma \qquad (1)$$

can be treated as Compton scattering of the pion off a virtual photon provided by the nucleus. The momentum transfer to the nucleus in the Primakoff reaction is very small ($Q^2 \ll m_\pi^2/c^2$). Since the Compton cross section contains the information about pion polarizabilitues, for their extraction one has to compare the measured differential cross section of the reaction (1) and the theoretically predicted one for a point-like spin-0 particle.

COMPASS is an experiment at the secondary beam of Super Proton Synchrotron at CERN. The purpose of this experiment is the study of hadron structure and hadron spectroscopy with high intensity muon and hadron beams [16]. The COMPASS setup provides unique conditions for the investigation of the Primakoff processes ([17]-[20]). It has silicon detectors up- and downstream of the target with a spacial resolution of about 10 μm for precise vertex position reconstruction and for the measurement of the pion scattering angle, an electromagnetic calorimeter (ECAL2) for the photon 4-momentum reconstruction (spatial resolution for $E > 100\ GeV$ is about 1.5 mm, energy resolution is $\sim 5\%$ for $E > 100\ GeV$) and two magnetic spectrometers for the determination of the scattered pion momentum ($dP/P < 0.5\%$). Hadron calorimeters and muon identification system are used for identification of secondary particles.

In COMPASS there is an unique possibility to use as the reference the reaction

$$\mu^- + (A,Z) \rightarrow \mu^- + (A,Z) + \gamma. \quad (2)$$

Since the muon is a point-like particle, the measured cross section and the calculated cross section have to be equal. This is the good way to estimate systematic uncertainties.

Studies of the Primakoff reaction at COMPASS were performed using data collected with the 190 GeV/c π^- beam and Pb target of 3 mm, 2+1 mm ($0.5X_0$) and 1.6 mm ($0.3X_0$) thickness during the pilot hadron run in 2004. Additional samples with Cu ($0.25X_0$), C ($0.12X_0$) and empty targets were used to study background processes and systematic errors. Sample with a 190 GeV/c μ^- beam and the 2+1 mm Pb target was also collected.

For the analysis the events with one primary vertex in the target region, one well measured outgoing track and one cluster in the central region of electromagnetic calorimeter were selected. The exclusivity of Primakoff events is guaranteed by cuts on the total energy and Q^2. In addition to electromagnetic scattering there is a diffractive scattering process with the same signature, for which the momentum transfer is not zero. Diffractive scattering produces a significant background in the region of large Q^2 while the peak at $Q^2 = 0$ corresponds to the Primakoff events. The contribution of pion diffractive scattering can be deduced from the comparison of the Q^2-distributions for pions and muons (see Fig. 1).

The comparison of data samples collected with different targets provides the possibility to measure the Q^2-behavior of the Primakoff signal and diffractive scattering background for different materials and to check the Z^2 dependence for the Primakoff cross section. In Fig. 2 one can see that Primakoff signal at $Q^2 = 0$ increases with increasing Z. The Primakoff cross section for different materials normalized to the cross section for lead is shown in Fig. 3. The dotted line shows the Z^2 -dependence. One can see that the measured values satisfy the Z^2 dependence for a wide range of Z. This proves that selection criteria effectively select Primakoff events and reject background events.

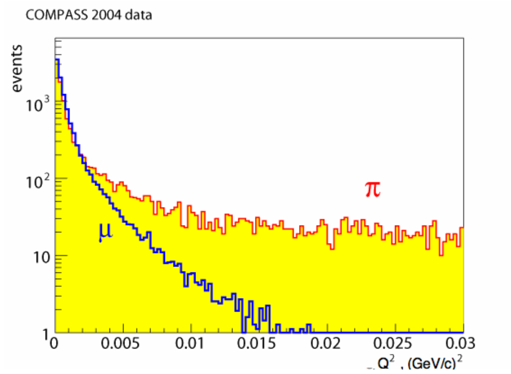

Figure 1. The Q^2-distribution of events produced with pion and muon beams.

In order to estimate possible sources of systematic uncertainties background processes which have the same signature in COMPASS detector as the Primakoff reaction were studied:

$$A^- \rightarrow B^- + 1 \; cluster \; in \; ECAL2 \; (E > 7 \; GeV),$$

where A^- is the beam particle, B^- is the scattered negatively charged particle and ECAL2 cluster is due to neutral particle. Two main types of of background channels were determined:

1. events with beam particles different from pion (A^- and B^- are μ^-, e^-, K^-, p^-). Background from muons can be reduced by rejection of the events with scattered particles identified as muons by the muon identification system. A cut on the P_t of scattered particle is effective against the electrons. Because of the relatively big mass and small admixture in the hadron beam, the kaon and proton backgrounds are negligible.

2. events with π^0, one soft decay photon of which was lost or two photons producing one cluster in ECAL2 (ρ-meson production and decay, beam kaons decay). These events can be rejected using the calorimeter information. Particularly, analyzing the cluster shape one can reject events with two photons in one cluster. One can also recover clusters of the lost soft photons analyzing the noise and pile-up clusters. The cut on $\pi^-\gamma$ in-

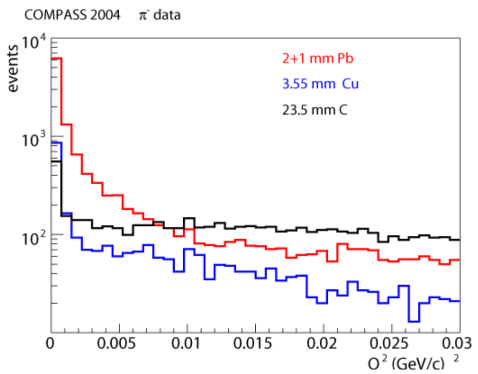

Figure 2. The Q^2 distributions for lead, copper and carbon tergets.

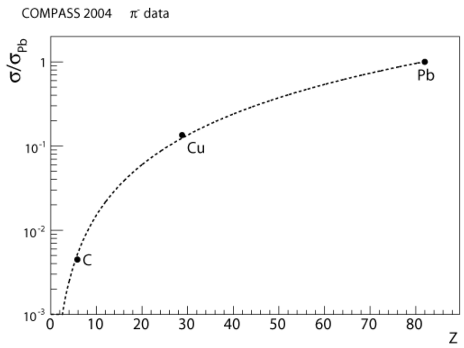

Figure 3. The Z-dependence of Primakoff cross section. The dotted line corresponds to Z^2 dependence.

variant mass is also effective to suppress π^0 from ρ-meson decays.

3. Possibility of future measurements at COMPASS.

The pilot hadron run 2004 has shown, that the COMPASS setup provides a good opportunity to measure pion polarizabilities with the precision inaccessible for previous experiments. To increase statistics and improve the quality of the collected data a number of modifications of the setup is necessary in 2009.

Capability of the upgraded DAQ system allows to increase beam intensities by the factor of 5 for the pion and by the factor of 10 for the muon beam. Optimized electron converter installed in the beam line will reduce the admixture of electrons in the pion beam. Threshold Cherenkov detectors (CEDAR) will be used for the beam kaon identification.

Radiative corrections for Compton vertex, multiple photon exchange, vacuum polarization, nuclear charge screening by electrons and nuclear form factor were calculated ([21]-[25]) and they turned out to be large for Pb. So the 0.5 X_0 Pb target will be replaced by a 0.3 X_0 Ni target to reduce the influence of the uncertainty of the radiative corrections, and improve the resolution in Q^2. Some modifications of trigger and muon identification systems to reduce systematic uncertainties will be also done.

With such modifications the data collected during 3 weeks of data taking will correspond to a total flux of 6×10^{11} for the pion and the muon beam. The corresponding statistical error of α_π measurement under assumption $\alpha_\pi + \beta_\pi = 0$ is about 0.4×10^{-4} fm^3. The lowest possible systematic uncertainty, based on the data to be collected with muon beam, is 0.2×10^{-4} fm^3. An independent measurement of α_π and β_π can be obtained with the statistical error 0.8×10^{-4} fm^3 With such a precision for the first time a significant test of theoretical predictions can be done.

The large statistics will also provide the possibility to measure the pion polarizability not only averaged in a certain range of kinematic variables, as it was done in previous experiments, but also to test how the polarizabilities depend on kinematical variables. For example such dependence is predicted by some NJL model [4].

4. Possible measurement of kaon polarizabilities

In addition to a precise determination of the pion polarizabilities, COMPASS has the chance

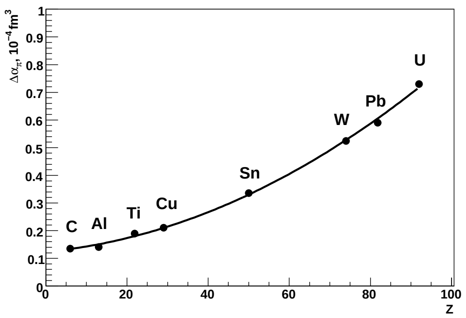

Figure 4. Radiative corrections $\Delta\alpha_\pi$ to α_π for different Z.

to perform the first measurement of Primakoff scattering of charged kaons and to estimate the kaon polarizability [26], [18]. The χPT prediction for α_K is $\alpha_K \approx \alpha_\pi/5$. The Primakoff cross section for kaons is $m_K^2/m_\pi^2 \approx 12.5$ times smaller than for pions and the fraction of kaons in the beam is only about 3%. But the contribution of the polarization term into the cross section is proportional to $m_{\pi,K}^3 \times \alpha_{\pi,K}$, that amplifiers the polarization effects for kaon in respect to pion by the factor of 9. After 3 weeks of data taking at COMPASS the value of α_K under assumption $\alpha_K + \beta_K = 0$ will be estimated with statistical accuracy about 0.2×10^{-4} fm^3.

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