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# Charged pion polarizability measurement at the COMPASS experiment

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**Abstract.** The pion electromagnetic structure can be probed in $\pi^- + (A, Z) \rightarrow \pi^- + (A, Z) + \gamma$ Compton scattering in inverse kinematics (Primakoff reaction) and described by the electric ($\alpha_\pi$) and the magnetic ($\beta_\pi$) 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 $\pi^-$ beam of 190 GeV during pilot run 2004. The obtained results were used for preparation of the new data taking which was performed in 2009.

## 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 ($\alpha_\pi$) and magnetic ($\beta_\pi$) 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 $(6 - 14) \times 10^{-4}\ fm^3$. At the moment knowledge of $\alpha_\pi$ and $\beta_\pi$ also has practical importance. Secondary pions at LHC experiments have energies up to 1 $TeV$ and radiative losses in medium with high $Z$ become comparable with ionizing losses. As far as the Compton cross section defines radiative losses, precise Monte Carlo simulation of pion interaction in electromagnetic and hadron calorimeters is difficult without taking into account effects of pion polarization. Behavior of the polarizabilities of the pion in a hot medium especially near the critical point, where phase transition and chiral symmetry restoration take place, is also interesting (see [6]).

Several attempts to measure these quantities were done (see [7]-[16]). But the obtained results are affected by large uncertainties and cannot be used for tests of theoretical predictions. New more precise measurements are needed.

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## 2 Primakoff reaction and pion polarizabilities

The Primakoff reaction

$$\pi^- + (A, Z) \rightarrow \pi^- + (A, Z) + \gamma \quad (1)$$

can be treated as Compton scattering of the pion off a virtual photon provided by the nucleus. Assuming that the mass of virtual photon is much smaller than the pion mass:

$$Q^2 \ll m_\pi^2, \quad (2)$$

one using the Weizsäcker-Williams approximation one can relate the Primakoff cross section and the Compton cross section:

$$d\sigma_{Prim} = d\sigma_{Comp} n(\omega_1, q_1) d\omega_1 dq_1, \quad (3)$$

where $\omega_1$, $q_1$ - the energy and the momentum of incoming photon in a anti-laboratory system and $n(\omega_1, q_1)$ is the equivalent photon density. The differential cross section is described by the formula:

$$\frac{d^3\sigma}{dQ d\omega_1 d(cos\theta)} = \frac{2\alpha^3 Z^2}{m_\pi^2 \omega_1} \times \frac{Q^2 - Q^2_{min}}{Q^4} |F_A(Q^2)|^2 \times$$
$$\times \left( F^{p.l.}_{\pi\gamma} + \frac{m_\pi \omega_1^2}{\alpha} \cdot \frac{\alpha_\pi (1 + cos^2\ \theta) + 2\beta_\pi cos\ \theta}{(1 + \frac{\omega_1}{m_\pi}(1 - cos\ \theta))^3} \right), \quad (4)$$

where $Q^2_{min} = (\frac{m_\pi \omega_1}{p_{beam}})^2$, $\theta$ the angle between the real photon and the virtual photon directions , $F_A(Q^2)$ the electromagnetic form factor of the nucleus ($F_A(Q^2) \approx 1$ for $Q \ll m_\pi$), $\alpha$ is the fine structure constant and $F^{p.l.}_{\pi\gamma}$ the differential Compton cross section for the scattering of photons on a point-like spin-0 particle. The cross section depends on $\alpha_\pi + \beta_\pi$ at forward angles and on $\alpha_\pi - \beta_\pi$ at backward angles. Since the Compton cross section contains the information about pion polarizabilitues, for their extraction a comparison of the measured differential cross section of the reaction (1) and the theoretically predicted one for a point-like spin-0 particle can be done.

## 3 COMPASS pilot hadron run 2004

COMPASS is an experiment at the secondary M2 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 [17]. The COMPASS setup provides unique conditions for the investigation of Primakoff processes ([18]-[21]). It has silicon detectors up- and downstream of the target with a spacial resolution of about 10 $\mu$m 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

$$\mu^- + (A, Z) \rightarrow \mu^- + (A, Z) + \gamma. \quad (5)$$

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 $\pi^-$ 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. A sample with a 190 GeV/c $\mu^-$ beam and the 2+1 mm Pb target was also collected.

The main Primakoff trigger selected events with very high photon energies. An energy threshold of about 90 $GeV$ was applied to the summed ECAL2 analogue signals. Veto counters for rejecting events with non-interacting beam particles and events with charged particles and photons emitted at large angles were also included into the trigger.

For the analysis 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).

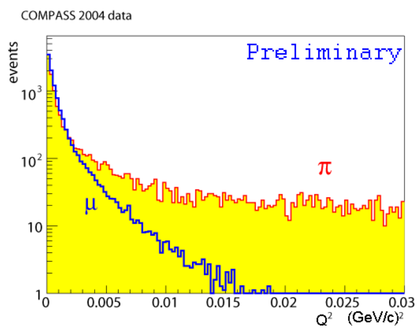


**Fig. 1.** The $Q^2$-distribution of events produced with pion and muon beams.

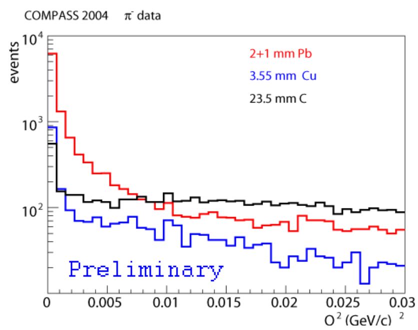


**Fig. 2.** The $Q^2$ distributions for lead, copper and carbon targets.

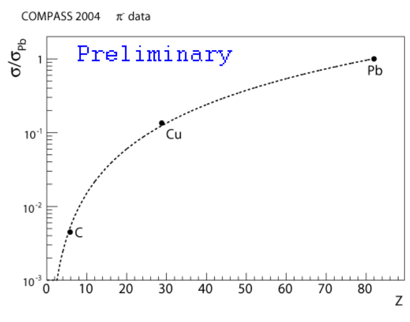


**Fig. 3.** The $Z$-dependence of Primakoff cross section. The dotted line corresponds to $Z^2$ dependence.

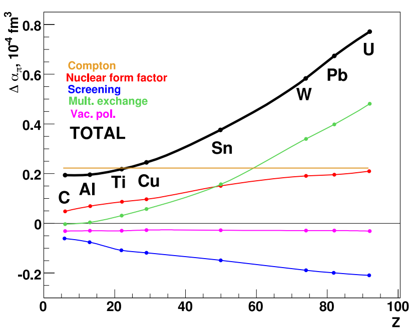


**Fig. 4.** Corrections to value of $\alpha_\pi$ coming from different sources.

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.

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 $\mu^-$, $e^-$, $K^-$, $p^-$): 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 $\pi^0$, one soft decay photon of which was lost or two photons producing one cluster in ECAL2 ($\rho$-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 $\pi^-\gamma$ invariant mass is also effective to suppress $\pi^0$ from $\rho$-meson decays.

## 4 COMPASS hadron run 2009

The pilot hadron run 2004 has shown, that the COMPASS setup provides good opportunity to measure pion polarizabilities precisely. New data taking for Primakoff studies was performed in October - November of 2009. Taking into account the experience obtained during the pilot run 2004 some changes in the setup and in the strategy of data taking were proposed [22].

Main Primakoff trigger was reorganized: only $12 \times 12$ central cells of ECAL2 were included into a new digital trigger. Such trigger organization kept the efficiency of Primakoff events selection and reduced significantly trigger rate produced by other events. The Primakoff trigger was operated with common threshold of about 60 $GeV$.

As it was shown in [23]-[27], the corrections to the Primakoff Born cross section for Pb become big, especially, the correction related to the nuclear form factor ($> 0.6 \times 10^{-4} fm^3$). The Z-dependence of such corrections as the radiative correction for the Compton vertex, vacuum polarization, double photon bremsstrahlung, nuclear charge screening by atomic electrons and nuclear form factor effects are shown in Fig 4. To decrease the dependence of the result on the corrections calculation a target material with smaller $Z$ was chosen. $Z$ should not be too small to avoid problems with significant diffractive background contribution and from this point of view materials with Z around 30 are most promising. Ni (Z=28) was used as the main material.

The spin-0 of $^{58}_{28}$Ni nucleus simplifies the estimation of the corrections. The optimal thickness of a Ni target results from a compromise between the number of Primakoff events which can be collected during limited time, and the quality of Primakoff signal and diffractive background separation. It was found that 0.3 $X_0$ is the optimal target thickness from this point of view.

Two Cherenkov differential counters (CEDARs) were used for beam kaon identification. The efficiency times the geometrical acceptance of the CEDAR was estimated to be around 35%. An electron converter (0.5 $X_0$ of Pb) was installed in the beam line to suppress contamination of electrons in the beam. The kinematic range of scattered particle identification was extended to small momenta ($P > 15\ GeV$ instead of $P > 20\ GeV$ in 2004). This is especially important for Primakoff events with a soft pion and a hard photon. Also the general performance of ECAL2 was greatly improved.

The Primakoff statistics collected in 2009 corresponds to an integrated flux of beam particles $2.5 \times 10^{11}$ of pions and $1.3 \times 10^{11}$ of muons. Corresponding the expected number of Primakoff events with photon energy above 95 $GeV$, satisfying the criteria mentioned above, is $3 \times 10^5$ for pions and $7 \times 10^5$ for muons. The collected statistics provides the possibility to extract the pion polarizability $\alpha_\pi$ under assumption $\alpha_\pi + \beta_\pi = 0$ with smaller statistical and systematic uncertainties than in the best previous measurements. A precise separate measurement of $\alpha_\pi$ and $\beta_\pi$ can also be done. Moreover, the polarizabilities can be measured in different kinematic ranges to access dynamic polarizabilities. There is also sensitivity the quadrupole polarizabilities $\alpha_{2\ \pi}$ and $\beta_{2\ \pi}$.

In addition to the study of Primakoff scattering off pions, COMPASS has a chance to perform the first observation of Primakoff scattering off charged kaons and to estimate the kaon polarizability [28], [19]. Taking into account that contamination of kaon in hadron beam is about 3%, the CEDAR efficiency of kaon identification is about 35% and that the Primakoff cross section depends on the particle mass as:

$$\sigma_{Prim} \sim \frac{1}{m^2}, \tag{6}$$

the statistics of Primakoff kaon events in kinematic range $E_\gamma > 60\ GeV$ in 2009 data sample can be estimated to be about 100 events. The main background processes are Primakoff scattering off pions (due to $K/\pi$ misidentification by CEDAR), kaon decay and $K^*(892)$ production and decay

$$K^- + (A,Z) \to K^*(892) + (A,Z) \to (A,Z) + K^- + \pi^0 \to (A,Z) + K^- + \gamma + \gamma. \tag{7}$$

New data taking for Primakoff physics is in the plans of the second phase of the COMPASS experiment (see COMPASS-II proposal [29]).

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