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**Prospects for hadron electromagnetic polarizability
measurement by radiative scattering on a nuclear target**

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abstract:

A Monte-Carlo simulation of hadron radiative scattering measurements on nuclei ($h + A \rightarrow h + \gamma + A$) by the Compton-Primakoff process is presented. The reaction with 40 GeV pion is studied and the results are compared with experimental data on carbon. Accuracy on the polarizability parameters expectable from higher energy measurements with currently available secondary beams of negatively or positively charged hadrons is discussed.

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1 Introduction

The electromagnetic polarizability of a system of charges is given by the induced electric and magnetic dipole moments of this system in response to an external electromagnetic field. The concept of electromagnetic polarizability is familiar from classical physics (see refs [1, 2] for example). The electric and magnetic polarizability parameters, reflect the electromagnetic rigidity of the system, characteristic of its internal structure and dynamics. The classical concept can be extended to quantum physics and it can be shown that the electromagnetic polarizability ranks among the fundamental constants of quantal systems together with their charge and magnetic moment [1, 3].

The interest in hadron electromagnetic (em) polarizability arose in the sixties [4, 5] when it was realized that the electric and magnetic polarizabilities were experimentally accessible and likely to provide unique informations on the electromagnetic structure of hadrons. The literature on the relationship of the polarizability parameters with the hadron structure is abundant. See refs [1, 3] for overviews on the issue and [49] for recent works on the subject. References to more specific theoretical works will be made in the following.

In a closely related field, nuclear polarizabilities have been investigated both theoretically and experimentally [7, 8], some of these works going much beyond the boundaries of nuclear physics [9]. Nuclear medium effects on the nucleon em polarizability have also been addressed recently [10, 11].

From the experimental point of view, several measurements of the electromagnetic polarizability coefficients have been performed or attempted on a few hadrons over the last few decades by various methods (see refs in [1, 2, 3]). In the most straightforward method, these coefficients can be obtained from precise measurements the angular dependence of γ -hadron Compton scattering differential cross sections. This method is suitable for stable particles and it has been used in several experiments on the proton [12, 13]. The neutron electric polarizability has been measured recently from the linear dependence of the n-nucleus total cross section on the electric polarizability coefficient [14]. A value of the neutron polarizability has also been deduced from γ -deuteron Compton scattering measurements [16] (see also refs [14, 15] for other experimental and theoretical references). Using another original method, an upper limit of the K^- polarizability has been deduced from X-ray measurements from Kaonic atoms [17].

The use of the Primakoff mechanism in radiative scattering experiments has been suggested long ago [18] (see also [19]). It can be applied to unstable hadrons available in secondary beams with suitable intensity. In this process, the projectile scatters on the flux of virtual photons provided by the coulomb field of a target nucleus. This method has been applied to the measurement of the pion polarizabilities, providing the only experimental values available to date for this particle [21] (see ref [20] for the status of the pion polarizabilities). In this process, the cross section depends on the squared atomic number of the target nucleus which may provide a useful amplification factor of the elementary Compton cross section. The physical interest for such measurements and more generally for the investigation of the electromagnetic properties of the hyperons have been emphasized recently [22, 23, 25], see also [24].

This paper reports on a simulation of some hadron radiative scattering measurements via the Compton-Primakoff process. The study was undertaken in the prospect of possible measurements of pion and Σ^- polarizabilities in good experimental conditions using the hyperon beam (WA89 experiment) at CERN. In these conditions, the π^- polarizability values could be significantly improved since the available pion beam intensity is larger

at Cern than it was at Serpukhov [21], and the angular range covered (in the hadron frame) could also be larger. In addition, some first measurements of the Σ^- hyperon polarizability could also be performed. The purpose was to investigate the sensitivity of the measured differential cross section to the electromagnetic polarizability parameters, and to evaluate the corresponding expectable accuracy on the experimental determination of these parameters, taking into account the instrumental effects in a very simple way, but realistic enough to provide significant results. It has been first attempted to reproduce some previously measured results and the investigation been extended next to other scenarii based on existing facilities offering secondary hadron beams at Cern. It must be emphasized that such a work should only be considered as a first step in the approach of the experimental issue. In particular, it cannot be substituted to a full simulation properly treating secondary particle interactions in the detectors as well as likely sources of physical backgrounds such as the $(hA \rightarrow h'\pi^0 A)$ channel, with a detector simulation package such as GEANT. Such an investigation is necessary for a reliable background estimate to be obtained. This is a key issue before final statements could be made about the feasibility of the measurements.

Reliable measurements could be performed only if a good enough resolution in four momentum transfer can be achieved. The required precision can be obtained by accurate tracking of the incident and scattered projectile. Efficient detection of the radiated photon is also necessary with accurate hit position measurement, implying a small granulometry (or a large distance from target) of the electromagnetic calorimeter.

The report is organized as follows. Some general features of the Compton-Primakoff cross section are first recalled in section 2 and presented the way they are used in the computing program. Next, the simulation program is described in section 3 whereas experimental accuracies are discussed in section 4. Section 5 is devoted to the simulation of Serpukhov experiment and comparison with the data. The simulation of higher energy measurements is then described and discussed in section 6. The results are summarized and the work concluded in 7.

2 Cross section for hadron radiative scattering

2.1 Interaction mechanisms

2.1.1 The electromagnetic process

Figure 1: *Lowest order interaction diagram for the Compton-Primakoff radiative scattering process.*

In electromagnetic radiative scattering of a hadron h on a nucleus A , $hA \rightarrow h'\gamma A$, the elementary process is the Compton scattering reaction illustrated on figure 1. This process is combined with the Primakoff mechanism in which the scattered photon is provided by the

nuclear Coulomb field of the target nucleus according to a distribution law discussed below, see refs [18, 26] and [1, 2, 3] about the Primakoff mechanism and the Compton scattering on hadrons respectively for a complete discussion of the issue.

It will be seen in section 2.2 how the cross section for this process depends on the electromagnetic polarizability parameters α_h and β_h of the hadron to the 2nd order in photon energy. Higher order corrections are outside the scope of the present study, they have not been considered here (see refs [27, 28, 29] on this subject).

Figure 1 shows the leading order diagram of the radiative scattering process. The reaction proceeds by scattering of a virtual photon provided by the coulomb field of the target nucleus, off the incident hadron. The $h\gamma$ intermediate system has an invariant square mass s_1 and recoils with a transferred 3 momentum $\vec{q}$ in the projectile reference frame. The transferred virtual photon has a virtual mass t with 4-vector components $\{\omega, \vec{q}\}$ in this frame. It is (quasi-)Compton scattered on the projectile and emerges on the mass shell in a real photon state with an energy ω' at angle θ in the final state. The quasi-Compton photon scattering kinematics is described in the appendix. The photon energy range to be covered depends on the hadron considered [2]. It should be small enough not to excite the first resonance of the hadron $\omega \ll \frac{M_h^2 - M_\pi^2}{2M_h}$ for the approximations on the cross section to be satisfied [3] otherwise energy dependent polarizability functions instead of coefficients should be considered and higher order terms in photon energy be taken into account in the cross section [31].

The relatively low energy of the scattered photon (typically a few tens or hundreds MeV in the case of interest) is boosted in the scattering process by the high velocity of the incident projectile to a much higher energy (in the GeV range for the cases considered here) in the laboratory frame. The detailed kinematics of the process will be discussed quantitatively in sections 5 and 6.

2.1.2 The strong interaction process

A noticeable complication of the method owes to the fact that a competing process exists. Indeed, radiative scattering can be induced by strong interaction as well, the radiated photon being associated to Pomeron exchange instead of photon exchange. The corresponding cross section does not depend of the electromagnetic features of the system and contributes to the measurement as an unwanted background only. The two mechanisms cannot be distinguished from the single measurement of the reaction products and the two amplitudes should thus be included in the cross section calculation or the hadronic contribution subtracted from the measurements by some extrapolation procedure [21]. To this purpose, the very different 4-momentum t dependence of the two cross section provide a mean to subtract the hadronic part: the electromagnetic process dominates the cross section at very small t values and becomes negligible elsewhere, whereas the strong interaction component becomes dominant beyond some minimum value of t weakly depending on the projectile. A typical value of the upper limit on t is $t \approx 10^{-3}(\text{GeV}/c)^2$. In addition, photons transferred at these t values are quasi real, matching the requirements of the Weissacker-Williams approximation [26].

2.2 The Compton-Primakoff cross section

The expression of the Compton-Primakoff cross section given below is a product of two terms, one originating from the Weissacker-Williams approximation and accounting for the

equivalent flux of virtual photons, and the other describing the elementary cross section for the Compton scattering process. A general derivation of the cross section for radiative scattering processes $hA \rightarrow h\gamma A$, where h is the incident hadron and A the target nucleus, can be found in ref [18] (see also [32]). The Compton scattering amplitude on an extended hadron is obtained from the low energy theorems of QED by developping the scattering amplitude to the second order in the photon energy ω [3] (see also [2, 15] and the quoted references).

The Weissacker-Williams approximation accounts for the equivalent photon flux provided by the Coulomb field of the target nucleus (see ref [26] for example). In this approximation, the triple differential cross section can be expressed following [18] as:

$$\frac{d^3\sigma}{dtds_1dcos\theta} = \frac{\alpha}{\pi} \frac{Z^2}{s_1 - m_h^2} \frac{t - t_{min}}{t^2} |F_A(t)|^2 \frac{d\sigma_{\gamma h}}{dcos\theta} \quad (1)$$

or equivalently in terms of the incident photon energy ω in the projectile frame:

$$\frac{d^3\sigma}{dtd\omega dcos\theta} = \frac{\alpha}{\pi} \frac{Z^2}{\omega} \frac{t - t_{min}}{t^2} |F_A(t)|^2 \frac{d\sigma_{\gamma h}}{dcos\theta} \quad (2)$$

In this relation, α is the fine structure constant, Z is the electric charge of the nuclear target, t is the four-momentum transferred to the target nucleus, s_1 is $\gamma\pi$ invariant mass squared in the final state, $F_A(t)$ is the electromagnetic form factor of the nucleus ($F_A(t) \simeq 1$ in the range of t considered), and $\frac{d\sigma_{\gamma h}}{dcos\theta}$ is the differential cross section for Compton scattering on the projectile hadron. The minimum four-momentum transfer t_{min} depends on ω according to [18]:

$$-t_{min} = \left(\frac{m_h\omega}{p_h}\right)^2, \quad (3)$$

p_h being the incident hadron momentum in the laboratory. See ref [33] for a discussion of the effective t_{min} value in relation with the atomic screening effect.

Note that the cross section goes as the square of the atomic number Z . This dependence cannot be fully exploited by using heavy nuclear targets to boost the elementary cross section since the target thickness has to be a reasonably small fraction of radiation length X_0 . This requirement severely limits the quantitative usefulness of the Z flexibility. Nevertheless, for a given fraction of X_0 , the target thickness will be a smaller fraction of the interaction length L_I for larger Z values ($\frac{X_0}{L_I} \approx \frac{A^{0.71}}{Z^2}$, see [36]) and the amount of hadronic background should decrease accordingly. High Z targets are thus certainly preferable.

The differential cross section for photon-hadron scattering can be written as the sum of a term corresponding to scattering by a point charge plus a term depending on the hadron structure [2, 3]:

$$\frac{d\sigma_{\gamma h}}{dcos\theta} = \left[\frac{d\sigma}{dcos\theta}\right]^{pt} + \left[\frac{d\sigma}{dcos\theta}\right]^{str} \quad (4)$$

The Born term cross section depends on the hadron spin. It is thus different for mesons and baryons, whereas the form of the structure dependent term is the same for all (elementary) hadrons, its value depending on the polarizability parameters of the hadron.

More explicitly, the above relation can be written as:

$$\frac{d\sigma_{\gamma h}}{dcos\theta} = \frac{2\pi\alpha^2}{m_h^2} \left\{ F_{\gamma h}^{pt}(\theta) + \frac{m_h\omega^2}{\alpha} \frac{\alpha_h(1 + cos^2\theta) + 2\beta_h cos\theta}{[1 + \frac{\omega}{m_h}(1 - cos\theta)]^3} \right\} \quad (5)$$

In this relation $\alpha = \frac{1}{137}$ is the fine structure constant, α_h and β_h are the electric and magnetic polarizability parameters respectively, and the angular function $F_{\gamma h}^{pt}(\theta)$ accounts for

the angular dependence of the differential Thomson cross section. For bosons it reads:

$$F_{\gamma h}^{pt}(\theta) = \frac{1}{2} \frac{1 + \cos^2 \theta}{\left[1 + \frac{\omega}{m_h}(1 - \cos \theta)\right]^2} \quad (6)$$

with $F_{\gamma h}^{pt}(0)=1$. The fermion case will be treated below.

A few remarks can be made about the general behaviour of this cross section. It can be seen from the above relation that the polarizability dependent term behaves as $(\alpha_h + \beta_h)$ at forward angles and as $(\alpha_h - \beta_h)$ at backward angles. This term is of the order of $\frac{m_h \omega^2}{\alpha} \alpha_h$ with respect to the point charge cross section (at forward angles or for small enough values of $\frac{\omega}{m_h}$).

It may also be noted that the bulk cross section goes as m_h^{-2} . It is thus expected to be a good order of magnitude smaller for scattering of baryons such as proton or Σ^- than for π . Aiming at the same counting statistics would thus require much longer measurements for baryons than for mesons, roughly in the ratio of their squared masses. However the polarizability dependent term is proportionnal to m_h thereby increasing the relative sensitivity of the cross section to this term for heavy particles, which tends to compensate the handicap of the lower cross section. Numerically, an estimate with relation 5 above shows that the point charge cross section at forward angles is of the order of 12 nb/sr and the polarizability about 7 nb/sr assuming $(\alpha_p + \beta_p)$ to be of the order of 10^{-3} fm^3 and 100 MeV incident photon energy for baryons such as proton or Σ (see refs [13, 34] for experimental values). In identical conditions for pion, the point charge cross section would be about 50 times larger (factor $\frac{m_p^2}{m_\pi^2}$), but the polarizability contribution would then be only about 10% of the point charge value. For a more realistic value of the $(\alpha_\pi + \beta_\pi)$ term, say 10^{-4} fm^3 [21] this relative contribution drops to the level of one percent. High counting statistics is thus required to reach an acceptable level of statistical significance for a proper polarizability determination. It will be seen below that the measurements are expectedly easier for baryons than for mesons in account of the above features.

2.2.1 mesons

The meson point charge cross section has a pretty simple expression. For pions, the $\pi A \rightarrow \pi \gamma A$ triple differential cross section is given by relation 2 above where the $\gamma \pi$ differential cross section can be written following ref [21]:

$$\frac{d\sigma_{\gamma\pi}}{d\cos\theta} = \frac{\pi\alpha^2}{m_\pi^2} \frac{|T|^2}{\left[1 + \frac{\omega}{m_\pi}(1 - \cos\theta)\right]^2} \quad (7)$$

with

$$|T|^2 = (1 + \cos^2\theta) \left[1 - \frac{2(\alpha_\pi + \beta_\pi)m_\pi}{\alpha} \omega\omega'\right] + \frac{2\beta_\pi m_\pi}{\alpha} (1 - \cos\theta)^2 \omega\omega' \quad (8)$$

a form which can be straightforwardly reduced to relations 5- 6. The scattered photon energy in the projectile frame ω' depends on ω according to the usual Compton relation.

$$\omega' = \frac{\omega}{1 + \frac{\omega}{m_\pi}(1 - \cos\theta)} \quad (9)$$

2.2.2 Baryons

For γ -baryon scattering, the differential cross section can be written to 4th order in ω as [3]:

$$\frac{d\sigma_{\gamma B}}{d\cos\theta} = \left[\frac{d\sigma_{\gamma B}^{pt}}{d\cos\theta}\right] - 2\pi e^2 \frac{\omega^2}{m} [\alpha_h(1 + \cos^2\theta) + 2\beta_h \cos\theta][1 - 3\frac{\omega}{m}(1 - \cos\theta)] + 0\omega^4 \quad (10)$$

with the same definitions as previously. The Compton scattering cross section for a point-like spin 1/2 charged particle is given by:

$$\frac{d\sigma_{\gamma B}^{pt}}{d\cos\theta} = \pi\left(\frac{e^2}{m}\right)^2 \{[1 - 2y + 3y^2 - 4y^3](1 + \cos^2\theta) + [y^2 + \left(\frac{\omega}{m}\right)^2 f(\theta)][1 - 3\frac{\omega}{m}(1 - \cos\theta)]\} + 0\omega^4 \quad (11)$$

with $y = \frac{\omega}{m}(1 - \cos\theta)$,

where $e^2 = \alpha$ in gauss units [2], and where ω is the photon energy in the baryon frame, and $f(\theta)$ is a function of the angle and of the anomalous magnetic moment of the particle [3].

The higher order Low term arising from π^0 exchange in the t channel is neglected here although it may contribute significantly to the cross section at large photon scattering angles [2, 3]. The conditions of validity of the above relations are discussed in ref [3].

2.2.3 General features of the Compton-Primakoff cross section

The general features of the triple differential cross section can be easily inferred from relation 2. The ω dependence is clearly dominated by the ω^{-1} factor and the cross section varies according to this law only slightly modified by the ω dependence of the angular distribution term. The t dependence is governed by the $\frac{t-t_{min}}{t^2}$ term which starts from zero at $t = t_{min}$, reaches a sharp maximum at $t = 2t_{min}$, and then decreases progressively as t^{-2} (note that t_{min} depends kinematically on ω).

The angular dependence described by relations 5, 8, and 10 above is smooth. The cross sections $\frac{d\sigma_{\gamma h}}{d\cos\theta}$ decrease continuously from a maximum value at zero degree down to a broad minimum at some angle in the backward region for mesons, close to 90 deg. for baryons (see sections 5, 6), and then rise again up to a backward maximum at $\theta = \pi$, this behaviour being governed by the ratio of parameters $\frac{\omega}{m_h}$. The dependence on the photon energy is important, it can be seen from the above equations that the contribution of the polarizability term to the cross section is larger for large photon energies and so is the sensitivity to α_h and β_h . Large photon energies should thus be favored as far as possible in the experiments as well as small t transfer values.

3 Simulation of Compton-Primakoff cross section measurements

3.1 Structure of the simulation program

The simulation program has been built in three main parts:

- 1) - Generation of the relevant dynamical and kinematical variable: $t, \omega, \cos\theta, \vec{p}_\gamma, \vec{p}_h$,
- 2) - Construction of the simulated experimental observables: $\vec{p}_{\gamma s}, \vec{p}_{hs}$,
- 3) - Reconstruction of the physical variables $t_s, \omega_s, \cos\theta_s$, by means of $\vec{p}_{\gamma s}, \vec{p}_{hs}$,
- 4) - Analysis of the simulated data.

In the first step, the relevant kinematic and dynamic variables $t, \omega, \cos\theta$, are generated according to their distribution laws and the kinematic transformation of the hadron and photon momenta to the lab frame is performed. This event generator is described in the next section.

In the next step, some experimental uncertainties, known from the instrumentation involved, or expected, are added to the momenta and angles of the incident and scattered hadron and photon generated in the first step, providing simulated experimental values of these variables.

In the last step, the sequence is inverted and the simulated experimental values of the scattering variables $(t_s, \omega_s, \cos\theta_s)$, are computed back from the simulated values of $\vec{p}_\gamma$ and $\vec{p}_h$ in the laboratory for each event and the simulated distributions are built. Details are given in the appendix.

The results can then be analyzed and the hadron polarizability parameters α_h and β_h be fitted to the simulated Compton angular distribution using the cross section formulas given above (2, 5, 8, 10). The analysis was performed by means of another program involving the optimization code MINUIT available from the CERN software library and callable from the PAW analysis software environment [35].

3.2 Event generator

The event generator has been built by means of relations 2 and 7 to 10 above. The variables t, ω , and $\cos\theta$ are generated according to their theoretical distributions. Such a Monte-Carlo generator is equivalent to computing the integral:

$$I_{hA \rightarrow h\gamma A}(\alpha_h, \beta_h) = \frac{\alpha Z^2}{\pi} \int_{\omega_{min}}^{\omega_{max}} \frac{d\omega}{\omega} \int_{-1}^1 d\cos\theta \frac{d\sigma_{\gamma h}(\cos\theta, \omega, \alpha_h, \beta_h)}{d\cos\theta} \int_{t_{min}(\omega)}^{t_{max}} dt \frac{t^2 - t_{min}(\omega)}{t^2} \quad (12)$$

where $\frac{d\sigma_{\gamma h}(\cos\theta, \omega, \alpha_h, \beta_h)}{d\cos\theta}$ is the elementary cross section as given by relation 5. The routine performing the event generation has been tested by comparing the generated distributions to the results of standard numerical integrations in relation 12. For given values of ω , t , and $\cos\theta$, the photon-hadron scattering kinematics is calculated. In the projectile frame a quasi-real photon specified by its 4-vector components $\{E, \vec{p}\} = \{\omega, \vec{q}\}$ with 4-momentum $t = \omega^2 - \vec{q}^2$ ($\vec{q}$ being the 3-momentum transferred from the nuclear target to the projectile) incident along the hadron recoil direction $\frac{\vec{q}}{|\vec{q}|}$ is scattered on the projectile and emerges as a real photon with energy ω' to an angle θ .

After the photon azimuthal scattering angle around the recoil direction has been randomly generated, all 4-vector components needed are calculated in the projectile frame and projectile-photon center-of-mass frame for the incident (virtual) and scattered (real) photon and for the projectile, using 4-vector algebra.

The computed photon and hadron momenta are then transformed to the lab system providing properly distributed and kinematically correct simulated values of $\vec{p}_\gamma$ and $\vec{p}_h$ to the experiment. Some useful algebraic details are given in the appendix.

4 Accuracy requirements

A major constraint set on the experimental accuracy occurs from the requirement that the scattering takes place in the pure coulomb region in order to ensure the reaction to be dominated by the electromagnetic interaction and to minimize contamination by strong

interaction induced radiative processes. The measured 4-momentum transfer must thus be accurate enough to allow a proper discrimination between coulomb and nuclear dominated regions, respectively below and above $t \approx 10^{-3} \text{ (GeV/c)}^2$. An upper limit to the acceptable accuracy can be set around $5 \cdot 10^{-4} \text{ (GeV/c)}^2$ from the existing elastic scattering data or calculations [30]. The coulomb peak at forward angles was shown to be well resolved in the Serpukhov experiment [21].

A rough estimate of the resolution can be made straightforwardly from the known resolutions of the tracking system, magnetic spectrometer and calorimeter, by noting that the upper limit in transverse momentum transfer associated to the above quoted upper limit on t is $q \approx t^{\frac{1}{2}} \approx 20\text{-}25 \text{ MeV}$. Each contribution to $\delta q_i = \delta(p_i \theta_i)$, $i = \gamma, h'$, arising from the individual inaccuracies over the angular and energy-momentum determination of the radiated photon and scattered hadron can be compared to the limit. Evaluating these respective contributions for a few sets of values representative of the kinematic range to be covered, shows that two contributions become particularly critical at high incident hadron energy. The contribution of the photon angle inaccuracy ($\delta q_\gamma = p_\gamma \delta \theta_\gamma$) is the most critical in the high photon energy range unless the position resolution of the calorimeter is small enough (which may imply a small granularity of the elements or a good position resolution preshower detector at a given distance from the target). It may represent several times the upper limit of q for say, 200 GeV hadrons and some realistic values for the position resolution of the calorimeter (see section 6). The other dominant contribution comes from the scattered particle (and beam) momentum resolution ($\delta q_{h'} = \theta_{h'} \cdot \delta p_{h'}$) which may also reach values of the order of the upper limit on q and beyond if the momentum measurement is to be performed by standard magnetic spectrometer technique for which $\delta p \approx \text{constant} \cdot p^2$.

The other two contributions due to δE_γ and $\delta \theta_{h'}$ can normally be kept below the acceptable limit. The first one because θ_γ remains small at all energies and δE_γ levels off to a minimum value at high energy. The uncertainty on the hadron scattering angle arises mainly from multiple scattering in the target, which decreases as $1/p$ [36], and from the spatial resolution of tracking detectors. It is expected to be smaller than $p_t^{had} \approx 15 \text{ MeV}$. In usual instrumental conditions these numbers can be kept smaller than the upper limit on $t^{1/2}$.

It must be noted however that the increasing contribution from the hadron momentum resolution can be reduced if the incident momentum particle is known with a good enough accuracy. Then, since the incident projectile and radiated photon momenta, are measured, and since the recoil nucleus momentum is negligible, the modulus of the scattered particle momentum can be deduced straightforwardly from the other two. Relevant figures will be given in section 6.

5 Simulation of the Serpukhov experiment

The results of the Serpukhov experiment performed with 40 GeV pions on ^{12}C have been used as a testground for the correctness of the simulation. In addition, this analysis has provided useful informations on the statistical significance of the experimental sample.

The parameters of the simulation, i.e., experimental resolutions, kinematical cuts and counting statistics have been taken from the available publications [37, 21]. The values used were:

- target thickness 0.25 radiation length,
- angular accuracy over scattered pion and radiated photon 0.12 mrad,
- electromagnetic calorimeter resolution $\frac{0.18}{\sqrt{E}}$ (ref [38]),

- kinematical cut: rejection of pion with momenta larger than 18 GeV,
- size of data sample $6 \cdot 10^3$ events,
- transferred photon energy range 0.1-0.6 GeV.

The test values of the polarizabilities used were $\alpha_\pi = 7 \cdot 10^{-4} fm^3$ and $\beta_\pi = -6 \cdot 10^{-4} fm^3$ close to the measured values and consistent with theoretical expectations [1, 23].

5.1 Kinematics

Figure 2: Scattered photon and pion kinematics in the laboratory as a function of the scattering angle in the projectile frame for radiative pion scattering on ^{12}C at 40 GeV. The curves show the scattered π and radiated γ (left and right resp.) momenta (in GeV) and angles (top and bottom resp.) for photon energy values $\omega = 100$ MeV (solid curves), 350 MeV (dashed), and 600 MeV (dotted), assuming a 4-momentum transfer $t = 10^{-4}$ (GeV/c) 2 . The two curves for each photon energy correspond to azimuthal photon angles of 0 and π around the recoil direction with respect to the $\vec{p}_h, \vec{q}$ scattering plane.

The radiative scattering kinematics is displayed on figure 2 for the $\pi + ^{12}C \rightarrow \pi + \gamma + ^{12}C$ reaction at 40 GeV. Scattering angles and momenta of the final state pion and photon in the lab are shown for a set of 3 photon energies ω spanning the useful range. For t transfer values considered here, the momentum carried away by the recoil nucleus is negligible and the incident pion total energy is shared between pion and photon in the final state to a good approximation.

It is seen on the figure that pion momenta in the laboratory cover a range from 40 GeV down to 4 GeV for the photon energy domain considered, while photon momenta cover the complementary domain from zero up to about 36 GeV. The pion angular range is confined within about 15 mrad, whereas the upper limit to most radiated photon angles is around 10 mrad except in the forward region where it diverges progressively to large angles reaching an upper limit of 420 mrad.

5.2 Results

The kinematical cut on the π momentum for a given photon momentum, suppresses momenta associated to scattering angles higher than some minimum value (see fig 2). The Compton angular distribution above some minimum angle is thus suppressed, the smaller the photon energy, the smaller the minimum angle. For the lowest photon energies involved, only the most backward angles are left. This can be seen on the (top left) kinematical curves of figure 2 where cutting π momenta above 18 GeV appears to cut part of the angular range to be measured over the full photon energy range considered. Only a restricted range covering backward angles is accessible in these conditions. It must be noted that for the lowest part of the photon energy range, say 0.1-0.2 GeV, even the most backward angles ($\cos\theta \approx -0.8$ to $-1.$), are partly cut out and the corresponding data should be corrected for this acceptance effect. Note that the π momentum cut off thresholds reported in refs [21, 37] are contradictory. A significantly better agreement of the simulation results with the experimental data is obtained with the value 18 GeV quoted in ref [37] and second ref [21], than with the value of 16 GeV given in first ref [21]. The former value has thus been used in the following.

Figures 3 through 5 show the distributions obtained. In these figures, blank histograms correspond to raw variables produced by the event generator before any instrumental effect was added and any kinematical cut applied, whereas shaded histograms correspond to final distributions affected by both instrumental resolution effects and kinematical cuts. Figure 3

Figure 3: Momentum (top) and angle (bottom) distributions of the scattered hadron (left) and photon (right) obtained from the simulation.

shows the final distributions obtained for the pion and photon momenta and angles. The cut on the photon momentum is the image of the cut on the pion momentum (edge folded with experimental resolution). It is also seen that the angular dynamics to be covered in these conditions are about 16 mrad and 10 mrad for pion and photon respectively.

Figure 4 displays the distributions obtained for the 4-momentum transfer t , the intermediate $\gamma\pi$ system invariant mass squared s_1 , the photon energy ω , and the photon

Figure 4: Distributions obtained for the four-momentum transfer t (top left), the invariant squared mass s_1 of the $\pi\gamma$ system (top right), the photon energy ω (bottom left), and the cosine of scattering angle in the projectile frame (bottom right), obtained from the event generator, prior and after detector effects and cuts are applied.

Figure 5: Simulated angular distributions of scattered photons in the projectile reference frame. The four photon energy windows are defined in the text.

scattering angle in the projectile frame, resulting from the event generator and after event reconstruction and cuts.

Figure 5 shows the angular distributions of events in the same 4 bins of photon energy as defined in refs [21, 39], i.e., 0.1-0.17, 0.17-0.23, 0.23-0.35, and 0.35-0.6 GeV. On this figure, the effects of the pion momentum cut expected from kinematics as commented above is clearly seen. At backward angles and for each photon energy bin, the distribution of simulated events (shaded area) follows the reference (theoretical) distribution provided by the event generator up to some angle, different for each ω bin, beyond which the cut effect sets in and the yield decreases rapidly to zero. It can be noticed that in ref [21] the equivalent experimental histograms (fig 3 in the quoted reference) are similar except over the angular range corresponding to the onset of the momentum cutoff. It can be supposed that this angular range not used in the analysis was not shown for convenience. It must be noted however that for the lowest ω bin, the contents of the two angular bins are significantly reduced by the π momentum cutoff as expected from previous considerations. This should distort the fitted values of polarizabilities unless properly corrected for. Figure 6 compares

Figure 6: *Simulated photon energy distribution (dashed line) compared to the result of the Serpukhov experiment (solid line).*

the simulated photon energy distribution with the experimental distribution measured in the Serpukhov experiment [21] for the same sample of 6000 events collected satisfying the cut conditions (this corresponds to about 50000 events generated). The agreement between the two distributions is very good, indicating that the main features of the experiment are properly treated in the program.

5.2.1 Analysis

The simulation has been used to investigate statistical and instrumental effects on the determination of α_π and β_π . The results of the analysis are summarized in table 5.2.1. Several samples of simulated events have been generated in different statistical and instrumental conditions, and the resulting double differential angular distributions have been fitted in various conditions of binning and angular dynamics. In particular the systematic errors introduced by the averaging effect over the photon energy inside the photon energy

Table 1: Results of the simulation of 40 GeV pion radiative scattering as described in the text. The electromagnetic polarizability parameters α_π and β_π are given in units 10^{-4}fm^3 . The values used in the simulation are $\alpha_\pi = 7$, $\beta_\pi = -6$. The lowest line gives the fit parameters obtained from the Serpukhov data.

Fits of simulation data					
fit #	events	bin size	α_π	β_π	χ^2/N
1	$6.5 \cdot 10^5$	0.02	7.36 ± 0.3	-6.5 ± 0.3	1.12
2	$6.5 \cdot 10^5$	0.02	7.1 ± 0.3	-6.2 ± 0.3	1.17
3	$5 \cdot 10^4$	0.02	10.6 ± 0.9	-9.4 ± 0.8	1.26
4	$5 \cdot 10^4$	0.2	7.3 ± 0.9	-7.2 ± 0.9	1.51
5	$5 \cdot 10^4$	0.2	7.1 ± 1.6	-4.7 ± 2.2	0.86
Fit of the Serpukhov experimental data					
6	$6 \cdot 10^3$	0.2	5.6 ± 1.6	-6.7 ± 2	2.68

windows used in [21], as well as those due to the effects of the angular binning, have been investigated.

The parameters fitted to the angular distributions were the two polarizability parameters α_π and β_π and a normalisation parameter for the cross section. The latter was varied freely in the fitting procedure. The trial values of the pion polarizability parameters were chosen close to the experimental values of [21], $(\alpha_\pi, \beta_\pi) = (7, -6)$ in units 10^{-4}fm^3 .

The first elementary test performed used a high statistics sample of $6.5 \cdot 10^5$ events, i.e. more than 10 times larger than in ref [21]. It was checked first that the averaging effect over the four photon energy windows defined as in [21] was negligible. A binning on $\cos\theta$ of 0.02 was used, and the instrumental effects were switched off by setting all resolution parameters to zero. The fitted values of the parameters for this configuration are given in set 1 of the table. They are statistically compatible with the generic values, within about 1σ . Therefore at this statistical level, the values of α_π and β_π fitted on the Compton angular distribution are expected to be significant despite the small (see section 2) statistical contribution of the polarizability terms to the cross section. This first test also provided an overall check of the simulation program and allowed further investigations to be performed on sound grounds.

Next the experimental resolutions were turned on one by one and fits to the full angular distributions were performed. At this incident energy and in the experimental conditions defined above, no contribution appeared to be dominant or having a specific effect on the fits (not shown). See discussion in section 4 however about the measurement of t .

The results with all contributions to the resolution involved are given in the parameter set 2 of table 5.2.1. As it could be expected the fitted values of α_π and β_π are again close to the generic values. Using a larger binning (10 or 20 bins) provides fitted values within ± 0.2 of the reference values.

The fitted parameter set 2 in the table should be considered as representative of the best results expectable from the data in these particular statistical and instrumental conditions, the latter having little effect on the fitted parameters in this case.

In a second step the same statistics as in the reference experiment has been generated, i.e. $5 \cdot 10^4$ events providing $6 \cdot 10^3$ events within the cuts defined above. The same study performed on the simulated data. Parameter set 3 of table 5.2.1 shows the corresponding results with a small (0.02) binning on $\cos\theta$. The polarizability parameters obtained from a fit over the full angular range overestimate the generic values by about 50%. Using the

Figure 7: *Simulated photon angular distributions and fits in the four photon energy windows as described in the text. The dashed line corresponds to the theoretical cross section for generic values of the polarizability parameters. The dotted lines results from the fit to the simulated data (set 4 in table 1).*

same data with a larger binning (10 or 20 bins) provides fitted parameters closer to the generic values (set 4). The fitted angular distributions are shown on figure 7.

Set 5 corresponds to the same sample fitted over the angular range limited by momentum cuts as in the reference experiment. It is shown on fig 8 (solid lines) where the results of the simulation are compared to the data. It can be seen that the simulated measurements are in fair agreement and statistically compatible with the measured data.

The reference experimental angular distributions [21] have also been fitted with the same program. The results are given by set 6 of the table. They are significantly different from those obtained in the original work [21] (see fig. 3 of the quoted reference). However it can be observed that visually the difference can hardly be appreciated. The χ^2 difference between the two calculations is 0.18 per point, thus hardly significant. This results illustrate the rather low level of significance of the parameter values to be obtained from the analysis of the available data and the necessity of more accurate measurements.

The experimental and simulated angular distributions are shown on figure 8 together with the fits corresponding to parameter set 6 (dash-dotted line) and to a calculation with polarizability parameters fixed to the values reported in [21] ($\alpha_\pi=8.5$, $\beta_\pi=-7.1$).

The present study has provided results in fair agreement with those of Antipov et al. and one may conclude that the level of statistics measured in the Serpukhov experiment has allowed to extract a significant value of $(\alpha_\pi + \beta_\pi)$ and of β_π .

Figure 8: Simulated photon angular distribution in the projectile frame without (dotted line) and with (dashed line) cuts on pion momentum as in the Serpukhov experiment, compared to these latter results (solid line). The two curves correspond to a calculation of the cross section using the same polarizability parameters as in the simulation (full curve) and to a fit of the polarizability parameter to the simulated data as described in the text (dashed curve).

6 Prospects for higher energy experiments

In this second part of the work, other scenarios have been considered for further studies of the electromagnetic polarizability of hadrons. In particular, the possibility of improving the accuracy of the polarizability parameter values of some known hadrons (p , π) has been considered together with the prospect of performing measurements on hadrons which polarizability parameter are unknown or poorly known so far.

6.1 CERN hyperon beam (WA89)

Secondary hadron beams are available at CERN which offer moderate to high intensities. These beams offer the possibility of performing polarizability measurements of unstable particles in good conditions. In the WA89 hyperon-beam experiment measurements could be made simultaneously on tagged π^- and Σ^- particles [40]. Simulation results are presented in this section for measurements on π^- and Σ^- in the WA89 experimental conditions.

6.1.1 Experimental conditions

The experimental resolutions have been taken from the recent results of the experiment. The experimental set-up has been assumed identical to the present configuration which would fit rather conveniently the requirements of the measurements considered at least for a first examination of the issue. The main resolution features involved in the simulation are the angular resolution the tracking system on the incident and scattered projectile trajectory,

and the position (angular) and energy resolution of the electromagnetic calorimeter. The calorimeter performances are very well known [41]. It is placed about 20 m downstream the target. The contribution of its position resolution to the transverse momentum inaccuracy is $p_\gamma \delta\theta_\gamma \approx 10^{-3} \sqrt{E_\gamma}$ in GeV, i.e., smaller than 15 MeV for 200 GeV projectiles. The angular resolution of the set of combined microstrip and mwpc detectors is better than 50 μ rad for tracks above say, 10 GeV, this number being conservative.

As we have quoted previously the 4-momentum resolution obtained when the module of the scattered hadron momentum is deduced from the incident particle and photon momenta making a colinearity approximation may be less inaccurate than the value obtained from direct measurement. This is as more true as one goes to high incident energies since the sensitive terms increase with the particle momentum. The Ω spectrometer resolution is $\frac{\delta P}{P} \approx 10^{-4}$, i.e., $\delta P \approx 4$ GeV for 200 GeV particles, raising to 9 GeV at 300 GeV. The hadron scattering angle is of the order of $\frac{m_h}{E_0}$, E_0 being the incident energy [42]. The transverse momentum inaccuracy arising from the scattered hadron momentum resolution $\theta_p, \delta p'$ is thus of the order of $10^{-4} m_h p'$. Using the proper kinematical values this contribution appears to amount to about 14 MeV for 200 GeV pions which is compatible with the requirement, and to about 110 MeV for Σ^- at the same momentum. This latter value is 5 times larger than the acceptable limit on q .

6.1.2 Results

The simulation has been based on the intensities currently available at the Cern hyperon beam, i.e., $5 \cdot 10^5 \pi^-$ and $2.5 \cdot 10^5 \Sigma^-$ per 2 second spill occurring every 14 s. This intensity is limited by the counting rate capability of the data acquisition system. A much lower rate is expected in a Primakoff experiment and a higher beam intensity could thus be afforded. A factor of three has been considered as realistic for medium Z targets. Note however that much higher pion beam intensities (up to $\approx 10^8 \text{s}^{-1}$) can be obtained on other beam lines at Cern.

Counting losses due to various sources of inefficiencies (tracking, DAQ dead time) have been taken into account rather conservatively. It amounts to about 60% of the event production rate. A carbon target has been assumed. The target thickness was taken the same as in ref [21]. Better results should be obtained with higher Z elements. A reference effective counting time of one month has been assumed.

In addition to the current experimental conditions [40, 44], it has been assumed a $\pm 1\%$ precision on the beam momentum measurement in accordance with the results expected from the dedicated equipment [43].

The cuts to be applied depend to a large extent on the trigger which may involve conditions on the photon, hadron scattering angle and momentum, probably a combination of these informations at different levels. In any case the events too close to the beam topology will not be measured. A cut on the scattered particle momentum has been set at $3\sigma_0$'s below the beam momentum value, σ_0 being the momentum resolution of the magnetic spectrometer to roughly account for a minimum trigger bias. Note that this cut is much more critical for heavier particles, i.e. baryons, than for mesons as it can be seen from the kinematics.

• π results

Improving our current knowledge of the pion electromagnetic polarizability is very important in account of the test of chiral symmetry breaking its measurement could provide. If the chiral symmetry is satisfied, one has strictly $\alpha_\pi + \beta_\pi = 0$. A non-zero value of this

Figure 9: Top: kinematics of the Σ^- radiative scattering reaction for a sample of relevant photon energy values ω and for $t=10^{-4}$ (GeV/c)², as a function of the photon-hadron scattering angle cosine in the projectile frame. Bottom: Σ^- scattering angle vs photon scattering angle in the laboratory.

quantity would thus provide a signature of chiral symmetry breaking. The present experimental value is $\alpha_\pi + \beta_\pi = 1.4 \pm 3.1_{stat} \pm 2.5_{sys} 10^{-4} \text{fm}^3$ [21], i.e., compatible with zero. The motivation is thus strong to improve the experimental accuracy.

The global features of the reaction kinematics at this momentum (not shown) are as follows. The hadron scattering angles are confined within a 3 mrad cone at forward angles. The photon angles are smaller than 10 mrad except at very forward Compton angles which suffer momentum cuts anyway. These angular dynamics fit easily into the acceptance of the experiment.

In the conditions specified above, a total sample of about $2.6 \cdot 10^5$ events are generated after inefficiency reduction, of which some 90% pass the momentum cuts and could be collected. The same 4 photon energy windows as in [21] have been used. A fit to the angular distributions leads to $\alpha_\pi = 7.74 \pm 0.38$ and $\beta_\pi = -6.77 \pm 0.36$ in units 10^{-4}fm^3 , to be compared to the generic values 7. and -6. respectively, in the same units. Note that the correct value of $\alpha_\pi + \beta_\pi$ is obtained. setting the polarizability parameters to zero leads to $\alpha_\pi = 0.61 \pm 0.42$ and $\beta_\pi = -0.68 \pm 0.4 10^{-4} \text{fm}^3$. Again the fitted values are found slightly off ($\approx 1.5\sigma$) the generic ones, the $(\alpha_\pi + \beta_\pi)$ value being good however.

We can thus conclude that a study of the pion electromagnetic polarizability in the above conditions should lead to a significant improvement of the statistical error of the current experimental value. However it must be kept in mind that this measurement of a very small effect is difficult, and that the sources of systematic errors and their consequences on the experimental uncertainty are not easy to quantify.

• Σ^- results

The kinematics is shown on figure 9. It is seen that the Σ^- scattering domain covers a

Figure 10: Angular distributions and fits obtained from the simulation of radiative scattering of 200 GeV Σ^- on a carbon target with (solid curve) and without (dashed curve) cuts. The curves correspond to a fit of the polarizability parameters α_{Σ^-} and β_{Σ^-} (dash-dotted), and to a calculation with the values used to generate the events (dotted). See text for details.

smaller momentum range extending between about 160 and 200 GeV and a narrower angular domain (< 0.8 mrad) than for π^- 's at the same incident momentum. The (complementary) photon energy range is also smaller than with pions (40 GeV vs 180 GeV) whereas the photon angles cover a much wider range than with pions, the useful part extending up to

say 50 to 100 mrad depending on the photon energy.

The simulation has been made for polarizability values compatible with theoretical estimates or calculations [22, 25], namely, $\alpha_{\Sigma^-} = 6 \cdot 10^{-4} \text{ fm}^3$, and $\beta_{\Sigma^-} = 0.6 \cdot 10^{-4} \text{ fm}^3$. The anomalous magnetic moment of the Σ^- used has been taken from ref [36].

In the experimental conditions defined above, the expected counting statistics is shown on figure 10, namely a sample of about 1500 events could be collected during the reference counting time. The angular distributions obtained within four 20 MeV wide photon energy windows between 40 MeV and 120 MeV have been analyzed using the proper theoretical shapes (see section 2.2). The values obtained are $\alpha_{\Sigma^-} = (7.9 \pm 1.6) \cdot 10^{-4}$ and $\beta_{\Sigma^-} = (1.6 \pm 2.1) \cdot 10^{-4}$ in fm^3 , for the angular distribution inside the cuts. The fit is shown on figure 10. These values fluctuate with the number of bins included in the fit around the onset of the cuts. They would become $\alpha_{\Sigma^-} = (6.4 \pm 1.24) \cdot 10^{-4}$ and $\beta_{\Sigma^-} = (-0.58 \pm 0.9) \cdot 10^{-4} \text{ fm}^3$ for the full angular distribution (no cut effect). Comparing with the previous values, shows clearly that the effect of the momentum cut on the scattered Σ^- is drastic and that this cut should be kept at as high a value as possible. Note that at least part of the angular distribution suffering the effects of the cuts can be recovered by correcting for this effect by means of the simulation, with a loss of accuracy however.

Therefore, despite a much smaller statistical sample of radiative scattering events than with the pion beam, the assumed Σ^- beam should lead to a reasonably significant determination of the Σ^- polarizability parameters, with a statistical error bar of the order of $0.2 \cdot 10^{-3} \text{ fm}^3$. This value could be improved with a higher beam intensity and/or a longer experiment.

6.2 The proton and Kaon case

• Proton

The proton case is interesting because it is experimentally the most studied and thus the best

Figure 11: Angular distributions and fits obtained from the simulation of radiative scattering of 200 GeV protons on a carbon target with the same definitions as in the previous figure.

known system with real photons on a proton target (see [13] and the references included). For this reason it has also been studied here for the sake of comparison of the results obtained by means of the Primakoff technique with those measured by Compton scattering of real photons.

The simulation has been made at the same incident momentum as above. Similar results would be obtained at other incident momenta, say below 300 GeV/c. It has been assumed a higher beam intensity as previously since a dedicated experiment should certainly offer higher count rates capability than used in the previous section. A beam intensity of 10^7s^{-1} has been assumed. All the other parameters defining the experimental conditions assumed in the simulation were the same as previously.

The most recent experimental values [13] have been used as polarizability parameters in the event generator, namely, $\alpha_p = 10.9 \cdot 10^{-4}$ and $\beta_p = 3.3 \cdot 10^{-4} \text{ fm}^3$. In the conditions defined above a sample of $0.9 \cdot 10^5$ events would be collected which analysis leads to the following values for the polarizability parameters: $\alpha_p = (10.2 \pm 0.3) \cdot 10^{-4}$, $\beta_p = (3.5 \pm 0.2) \cdot 10^{-4} \text{ fm}^3$ for the full angular distribution, i.e. assuming that the differential cross section of the angular region affected by the momentum cut can be corrected (by simulation). The correct values are then retrieved to within about 2σ . Limiting the fit to the data not affected by the cut (fig 11), one gets $\alpha_p = (8.8 \pm 0.4) \cdot 10^{-4}$, $\beta_p = (3.4 \pm 0.35) \cdot 10^{-4} \text{ fm}^3$. The missing part of the angular distribution would then induces a significant underestimate of the electric polarizability value.

A study of the radiative primakoff scattering of the proton would therefore allow to collect a sample of events covering a wide photon energy range from around 40 MeV up to beyond 120 MeV and a wide angular distribution of scattered photons (see figure 11). The analysis of this sample should lead to a statistical accuracy of about $\pm 0.2\text{-}0.4 \cdot 10^{-4} \text{ fm}^3$, i.e., several times better than obtained in the most recent measurement [13]. In addition it would provide some grounds for a detailed comparison between the direct measurements with real photon and the undirect measurement technique via the Primakoff process.

• Kaon

The Kaon polarizability would also be very interesting to measure. However, the Compton cross-section for the Kaon is several times smaller than for the pion, and the expectable beam intensity, namely less than about 5% of the pion intensity at energies lower than about 250 GeV where proper K identification can be achieved, is also very small. In addition, small values of α_K and β_K are expected from a recent theoretical estimate [45], see also [46]. A study of the kaon polarizability cannot thus be considered in the beam conditions defined in the above section 6.1.

An estimate of the expectable experimental accuracy has been obtained assuming a secondary beam intensity of 10^7 pions and $3 \cdot 10^5$ Kaons per second at 200 GeV and in the same experimental conditions as previously. These beam conditions are currently available at Cern. The assumed values of the polarizability parameters were $\alpha_K = 3.5$ and $\beta_K = -2$ in 10^{-4} fm^3 units, compatible with the theoretical values given in [45]. The photon energy range has been limited to 60-300 MeV, i.e., somewhat below the first K^* excited state.

In such conditions about 10^4 events would be recorded and the kaon parameters would be obtained with a fairly good accuracy, namely $\alpha_K = 3.55 \pm 0.6$ and $\beta_K = -2.85 \pm 0.7 \cdot 10^{-4} \text{ fm}^3$. These accuracies are hardly worse than those obtained for the proton above. The latter was obtained with a much higher beam intensity but a much smaller photon energy range and a twice larger Compton cross section, the whole accounting for the observed difference between the results.

7 Summary and conclusion

This study has shown that a simulation of the hadron radiative scattering via the Primakoff-Compton process, treating properly the dynamical and kinematical degrees of freedom of

the process, can pretty well account for the experimental results obtained with 40 GeV pions on a carbon target.

It has also been seen that the current hyperon beam experiment at Cern (WA89) could perform measurements of the π^- and Σ^- electromagnetic polarizability, improving the statistical uncertainty of the former and providing a first measurement of the latter.

Some measurements on the proton with a beam around 200-300 GeV would provide an accurate set of data which would significantly improve the current accuracy on the polarizability parameter values. In addition these values could be used as a basis for a useful comparison of the Primakoff induced reaction with real photon scattering.

The Kaon polarizability would also be very interesting to investigate. Although the kaon component of secondary charged beams is small, we have shown that a high intensity secondary beam of positively charged tagged particles would allow to achieve a high quality measurement of the proton, pion and kaon polarizabilities in a single step.

The p, π^+, K^+ polarizabilities would most conveniently be measured altogether in a single experiment by means of a secondary tagged beam of 160-200 GeV in which the ratio of relative intensities would be about 1/1/0.05 respectively. A proper tagging could be achieved by means of a beam RICH such as described in [47].

Finally it must be emphasized that the interest in radiative scattering studies is not limited to the single electromagnetic polarizability measurements, but also includes topics such as higher energy Compton scattering and its relationship with the interaction mechanism and the hadronic structure of the photon [48] and radiative excitation of resonances (see refs [24, 49, 50] for examples). The interest and applications of the Primakoff process itself also extend much beyond the single topic treated in this report [18, 51].

The numerical computations have been performed on a DEC5000/200 workstation. The simulation and fitting programs, and the command file environment operating under PAW are available on request from the author.

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APPENDIX

This section provides some details on the kinematical calculations performed in the program and some useful algebraic relations on the kinematics involved are given.

After some values of the variables $t, \omega, \cos\theta$, and ϕ are generated by a call to the event generator (see section 3.2), which completely determines the kinematics of the system, the following sequence of calculation and transformations is performed:

- 1) - The recoil momentum module q and angle θ_r of the projectile(target) in the projectile(target) frame is computed using standard 2-body kinematics relations. This angle is to be used for rotating the axis to return to the lab frame later.
- 2) - The scattered photon momentum in a frame which Oy axis is taken colinear with the incident photon direction ($\vec{q}$) is computed. This frame is rotated by $(\theta_r - \frac{\pi}{2})$ with respect to the projectile frame, θ_r being the recoil angle with respect to the incident target momentum in the projectile frame. The process consists of a quasi-Compton scattering $\gamma^* h \rightarrow \gamma h$ of an incident virtual γ^* with energy ω and virtual squared mass $t = \omega^2 - \vec{q}^2$ in the initial state being scattered on the projectile to a real photon γ final state with energy ω' , at a scattering angle θ in this frame.

Solving the kinematic equations for this process leads to the relation:

$$\omega' = \frac{\omega(1 + \frac{\omega^2 - q^2}{2m_h\omega})}{1 + \frac{\omega}{m_h}(1 - \frac{q}{\omega}\cos\theta)} \quad (13)$$

with the above definitions. Note that the usual Compton relation is retrieved for $t=0$.

This relation is inverted to calculate $\cos\theta$ in the event reconstruction process.

- 3) - The scattering variables are computed in the γh center of mass. Specifying the kinematic variables with an asterisk in this latter frame and with a prime for final states, the relevant relations are:

- in the entrance channel:

$$\omega^* = \frac{t + m_h\omega}{\sqrt{s_1}} \quad (14)$$

- in the exit channel:

$$\omega'^* = \frac{s_1 - m_h^2}{2\sqrt{s_1}} \quad (15)$$

with

$$s_1 = m_h^2 + t + 2m_h\omega \quad (16)$$

The scattering angle in the γh center-of-mass system is given in terms of the known quantities by:

$$\cos\theta^* = \frac{\omega^*\omega'^* - \omega\omega'(1 - \frac{q}{\omega}\cos\theta)}{\omega^*q^*} \quad (17)$$

- 4) - The momentum components of $\vec{p}_h$ and $\vec{p}_\gamma$ are then computed sequentially:
 - first in this ($h\gamma$ center of mass) frame using the above calculated quantities and the azimuthal scattering angle ϕ randomly generated with a uniform distribution,
 - next in the rotated projectile frame (used in 2) above) by a (Lorentz) translation of $-\vec{q}$ along the z axis,
 - next in the projectile frame by a sequence of two rotations of $(\frac{\pi}{2} - \theta_r)$ around Ox' bringing

the z axis of the rotated frame colinear to the projectile lab z axis (incident momentum direction), and of ϕ around Oz to bring Oy back along the chosen reference direction, in principle a magnetic field.

- and finally in the laboratory by an ultimate Lorentz transform, providing the kinematically correct values of the momenta produced by the Compton-Primakoff mechanism.

Each particle invariant mass is computed after each change of reference frame to cross-check both the correctness and the accuracy of the computation. Most of the program modules are written in double precision for the accuracy requirement to be satisfied.

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