Deeply virtual Compton scattering off Helium nuclei with positron beams

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The relevance of using positron beams in deeply virtual Compton scattering (DVCS) off ^{4}He and ^{3}He is addressed. The way the so-called $d-$term could be extracted from the real part of the relevant Compton form factor, using as an example coherent DVCS on ^{4}He, is summarized, and the importance and novelty of this measurement is described. Analogous measurements are addressed for ^{3}He tagets, which could be very useful even in a standard unpolarized setup, measuring beam spin asymmetries and charge beam asymmetries only. The role of incoherent DVCS processes, in particular tagging the internal target by measuring slow recoiling nuclei, and the unique possibility offered by positron beams for the investigation of Compton form factors of higher twist, are also briefly addressed.

Introduction

The possibility to shed light on the EMC effect, i.e., the nuclear modifications of the nucleon parton structure (1, 2), as well as the feasibility to distinguish coherent and incoherent channels, have been recently experimentally demonstrated by the CLAS collaboration at JLab using a ^{4}He gaseous target (3, 4). Those measurements have led to a growing interest on nuclear deeply virtual Compton scattering (DVCS). Let us analyze the impact that measurements of positron initiated DVCS on ^{4}He and ^{3}He may have, separately for the coherent an incoherent channels.

Coherent DVCS

To fix the ideas on how positron beams could help in this field, let us think first to coherent DVCS off ^{4}He. We recall that ^{4}He has only one Compton Form Factor (CFF), corresponding to one chiral-even generalized parton distribution (GPD) at leading twist. In the EG6 experiment of the CLAS collaboration, Ref. (3), the crucial measured observable was the beam-spin asymmetry A_{LU}, which can be extracted from the reaction yields with the two electron helicities ($N^{\pm}$):

$$A_{LU} = \frac{1}{P_B}\frac{N^+ - N^-}{N^+ + N^-}, \tag{1}$$

where P_B is the degree of longitudinal polarization of the incident electron beam.

In the accessible phase-space of the EG6 experiment, the cross section of real photon electroproduction is dominated by the BH contribution, while the DVCS contribution is very small. However, the DVCS contribution is enhanced in the observables sensitive to the interference term, *e.g.* A_{LU}, which depends on the azimuthal angle ϕ between the (e, e') and $(\gamma^*, ^4\text{He}')$ planes. The asymmetry A_{LU} for a spin-zero target can be approximated at leading-twist as

$$A_{LU}(\phi) = \frac{\alpha_0(\phi)\,\Im m(\mathcal{H}_A)}{den(\phi)}\,, \tag{2}$$

$$\begin{aligned} den(\phi) &= \alpha_1(\phi) + \alpha_2(\phi)\,\Re e(\mathcal{H}_A) \\ &+ \alpha_3(\phi)\left(\Re e(\mathcal{H}_A)^2 + \Im m(\mathcal{H}_A)^2\right). \end{aligned} \tag{3}$$

The kinematic factors α_i are known (see, e.g., Ref. (5, 6)).

In the experimental analysis, using the different contributions proportional to $\sin(\phi)$ and $\cos(\phi)$ in Eq. (3), both the real and imaginary parts of the so-called Compton Form Factor $\mathcal{H}_A$, $\Re e(\mathcal{H}_A)$ and $\Im m(\mathcal{H}_A)$, respectively, have been extracted by fitting the $A_{LU}(\phi)$ distribution. Results of the impulse approximation calculation of Ref. (7), where use is made of state-of-the-art ingredients for the description of the nuclear and nucleon structure (older calculations can be found in (8, 9)), are shown together with the data of Ref. (3) in Figs. 1 and 2. Big statistical errors are seen everywhere in the data but, in particular, the extracted $\Re e(\mathcal{H}_A)$ is less precise than $\Im m(\mathcal{H}_A)$, due to the small coefficient α_2 in Eq. (3).

Forth-coming data from JLab with the upgraded 12 GeV electron beams, using also a recoiling detector developed by the ALERT run-group (10), will improve the statistical precisions. Together with refined realistic theoretical calculations, in progress for light nuclei, the new data will help to unveil a possible exotic behavior of the real and imaginary part of $\mathcal{H}_A$. Nonetheless, the extracted $\Re e(\mathcal{H}_A)$ will be always less precise than $\Im m(\mathcal{H}_A)$, intrinsically, due to the small coefficient α_2 in Eq. (3). A precise knowledge of $\Re e(\mathcal{H}_A)$ for light nuclei would be instead crucial. Positron beams would guarantee this achievement: as a matter of fact, combining data for properly defined asymmetries measured using electrons and positrons, the role of $\Re e\mathcal{H}_A$ would be directly accessed.

One should notice that, between the quantities appearing in the above equations and the cross sections defining the generic photo-$e^{\pm}$production cross section in the following schematic general expression, previously given in this White Paper,

$$\begin{aligned} \sigma^e_{\lambda 0} &= \sigma_{BH} + \sigma_{DVCS} + \lambda\tilde{\sigma}_{DVCS} \\ &+ e\sigma_{INT} + e\lambda\tilde{\sigma}_{INT}\,, \end{aligned} \tag{4}$$

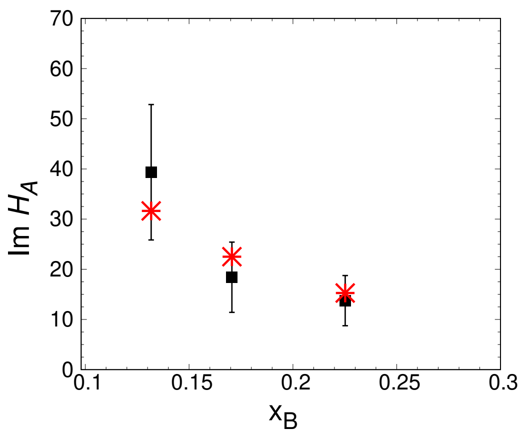

Fig. 1. The imaginary part of the CFF measured in coherent DVCS off ^{4}He. Data from Ref. (3); calculations (red crosses) from Ref. (7)

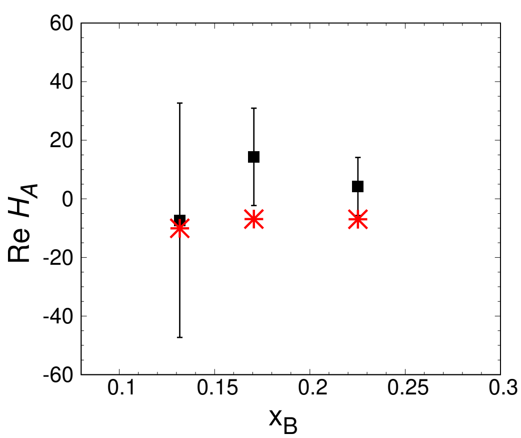

Fig. 2. The real part of the CFF measured in coherent DVCS off ^{4}He. Data from Ref. (3); calculations (red crosses) from Ref. (7).

the following relations hold:

$$\begin{aligned} \sigma_{BH} &\propto \alpha_1(\phi)\,, \\ \sigma_{DVCS} &\propto \alpha_3(\phi)\big(\Re e(\mathcal{H}_A)^2 + \Im m(\mathcal{H}_A)^2\big)\,, \\ \sigma_{INT} &\propto \alpha_2(\phi)\,\Re e(\mathcal{H}_A)\,, \\ \tilde{\sigma}_{INT} &\propto \alpha_0(\phi)\,\Im m(\mathcal{H}_A)\,, \end{aligned} \quad \textbf{(5)}$$

while $\tilde{\sigma}_{DVCS}$ is proportional to a term kinematically suppressed at JLab kinematics, which depends on higher twist CFFs.

From a combined analysis of data taken with polarized electrons and/or positrons, one could access all the five cross sections in Eq. (4). We stress in particular that, using just unpolarized electrons and positrons, $\Re e(\mathcal{H}_A)$ would be directly accessed, building charge beam asymmetries. Let us briefly analyze why the knowledge of $\Re e\mathcal{H}_A$ would be very important for nuclei. Formally one can write, for the quantities $\Re e(\mathcal{H}_A)$ and $\Im m\mathcal{H}_A$ shown in Figs. 2 and 1 respectively (11):

$$\Re e\mathcal{H}_A(\xi,t) \equiv \mathcal{P}\int_0^1 dx H_+(x,\xi,t)C_+(x,\xi)\,, \quad \textbf{(6)}$$

and

$$\Im m\mathcal{H}_A = -\pi H_+(\xi,\xi,t)\,, \quad \textbf{(7)}$$

with:

$$H_+ = H(x,\xi,t) - H(-x,\xi,t)\,, \quad \textbf{(8)}$$

amd

$$C_+(x,\xi) = \frac{1}{x+\xi} + \frac{1}{x-\xi}\,, \quad \textbf{(9)}$$

with $H(x,\xi,t)$ being the chiral-even leading twist GPD.

Moreover, it is also known that $\Re e(\mathcal{H}_A)$ satisfies a once subtracted dispersion relation at fixed t and can be therefore related to $\Im m\mathcal{H}_A$, Ref. (12–15), leading to

$$\Re e\mathcal{H}_A(\xi,t) \equiv \mathcal{P}\int_0^1 dx H_+(x,x,t)C_+(x,\xi) - \Delta(t)\,. \quad \textbf{(10)}$$

One notices that, in contrast to the convolution integral defining the real part of the CFF in Eq. (6), where the GPD enters for unequal values of its first and second arguments, the integrand in the dispersion relation corresponds to the GPD where its first and second arguments are equal. The subtraction term $\Delta(t)$ can be related to the so-called $d-$term and accurate measurements, supplemented by precise calculations, would allow therefore to study this quantity in nuclei, for the first time. This $d-$term, introduced initially to recover the so-called polinomiality property in DDs approaches to GPDs modelling (16), has been related to the form factor of the QCD energy momentum tensor (see e.g. Ref. (17)). It encodes information on the distribution of forces and pressure between elementary QCD degrees of freedom in the target. For nuclei, it has been predicted to behave as $A^{7/3}$ in a mean field scheme, either in the liquid drop model of nuclear structure (18) or in the Walecka model (19). None of these approaches makes much sense for light nuclei, for which accurate realistic calculations are possible. Using light nuclei one would therefore explore, at the parton level, the onset and evolution of the mean field behavior across the periodic table, from deuteron to ^{4}He, whose density and binding are not far from those of finite nuclei.

In this sense, coherent DVCS off ^{3}He targets acquire an important role: an intermediate behavior is expected between that of the almost unbound deuteron system and that of the deeply bound alpha particle. The formal description of coherent DVCS off ^{3}He follows that already presented for the proton, a spin one-half target, in terms of CFFs and related GPDs. Properly defining spin dependent asymmetries. Realistic theoretical calculations are available for GPDs in Ref. (20–23) and are in progress for the relevant CFFs, cross sections, and asymmetries, representing an importanmt support to the planning of measurements. One couuld object that the use of ^{3}He, either longitudinally or transversely polarized, represents at the moment a challenge, either with electron or positron beams. Actually beam-charge asymmetries, built using electron and positron data, would represent, even with unpolarized ^{3}He targets and unpolarized beams, a possible access to $\Re e\mathcal{H}_A(\xi, t)$, as previously described for ^{4}He, with the same potential to explore the "d-"term for this relevant light nucleus.

Incoherent DVCS

A subject aside is represented by the incoherent DVCS off Helium nuclei, i.e., the process where the DVCS occurs on a bound-nucleon, which is ejected from the nucleus. Therefore, the bound-nucleon's CFFs can be accessed, its GPDs, in principle, extracted and, ultimately, its tomography is obtained. This would provide a pictorial representation of the realization of the EMC effect and a great progress towards the understanding of its dynamical origin. As already stressed, this channel has been successfully isolated in the EG6 experiment of the CLAS collaboration at JLab (4) and a first glimpse at the parton structure of the bound proton in the transverse coordinate space is therefore at hand (see the recent impulse approximation calculation in Ref. (24) for a theoretical description of the recent data with conventional realistic ingredients). The program at JLab 12 includes an improvement of the accuracy of these measurements, in particular, for the first time in DVCS, tagging the struck nucleon using the detector developed by the ALERT run group (25). This would allow to keep possible final state interactions, relevant in principle in this channel, under control. Measurements performed with electron and positron beams would allow for example the measurement of the $d-$term for the bound nucleon, either proton in ^{3}He (tagging 2H from DVCS on ^{3}He) or in ^{4}He (tagging ^{3}H from DVCS on ^{4}He) or neutron in ^{4}He (tagging ^{3}He from DVCS on ^{4}He). Modifications of the $d-$term of the nucleon in the nuclear medium, studied e.g. in Ref. (19), would be at hand, as well as a glimpse at the structure of the neutron in the transverse plane, complementary to that obtained with deuteron targets.

Beyond a chiral even GPDs description of DVCS on ^{4}He

As a last argument, we note that, from the measurement of beam spin asymmetries built using cross sections measured with polarized electrons and positrons in coherent DVCS off ^{4}He, the cross sections $\tilde{\sigma}_{DVCS}$ and $\tilde{\sigma}_{INT}$, appearing in Eq. (4), could be independently accessed. This would allow, for the first time, to study the other leading twist CFF of a spinless target, the so called gluon transversity GPD H_T, giving a corresponding name to the CFF $\mathcal{H}_T$, appearing in $\tilde{\sigma}_{DVCS}$. In Ref. (6), it is shown how the contribution of $\mathcal{H}_T$ to the cross section occurs through an interference between twist-two and effective twist-three CFFs. A first glimpse at this complicated interrelation would be obtained for a spinless target, in particular for a nuclear target, for the first time. As for any other gluon-sensitive observable, data for the cross section $\tilde{\sigma}_{DVCS}$ would be a perfect tool to study gluon dynamics in nuclei. For example, a comparison with calculations performed in an Impulse Approximation scheme, where the relevant nuclear degrees of freedom are colorless nucleons and mesons, with gluons confined within them, would have the potential to expose possible exotic gluon dynamics in nuclei. This would be a pretty new possibility, complementary to that planned at JLab with 12 GeV, using exclusive vector meson electroproduction off ^{4}He (25). Such an interersting behavior would be very hardly seen using electrons only, due to the strong kinematical suppression of $\tilde{\sigma}_{DVCS}$ with respect to the other contributions in Eq. (4).

Conclusions

The unique possibilities offered by the use of positron beams in DVCS off three- and four-body nuclear systems have been reviewed. Summarizing, we can conclude that the main advantages will be:

- in coherent DVCS off ^{3}He and ^{4}He, using polarized electrons and unpolarized positrons, the real part of the chiral even unpolarized CFF would be measured with a precision comparable to that of the imaginary part, providing a tool for the study of the so called d term and to the distribution of pressure and forces between the partons in nuclei, a new way to look at the nuclear medium modifications of nucleon structure;

- in incoherent DVCS off ^{3}He and ^{4}He, possibly tagging slow recoiling nuclear systems, the same programme could be run for the bound proton and neutron;

- using polarized ^{3}He targets, a more complicated setup for the moment, spin dependent and parton helicity flip CFFs would be accessed for the first time for a nucleus, in both their real and imaginary parts;

- coherent DVCS off ^{4}He, initiated with polarized positrons, would allow a first analysis of nuclear chiral odd CFFs and GPDs, with higher twist contaminations suitable to tenptatively explore gluon dynamics in nuclei.

To conclude, a program of nuclear measurements with positron beams would represent therefore an exciting complement to the experiments planned with nucleon targets, and to those planned with nuclear targets and electron beams.

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