Physics Opportunities at ELFE

Paul Hoyer
Nordita
Blegdamsvej 17, DK–2100 Copenhagen Ø, Denmark

Abstract

I review some central physics opportunities at the 15...30 GeV continuous beam electron accelerator ELFE, proposed to be built in conjunction with the DESY linear collider. Our present detailed knowledge of single parton distributions in hadrons and nuclei needs to be supplemented by measurements of compact valence quark configurations, accessible through hard exclusive scattering, and of compact multiparton subsystems which contribute to semi-inclusive processes. Cumulative ($x > 1$, $x_F > 1$) processes in nuclei measure short-range correlations between partons belonging to different nucleons in the same nucleus. The same configurations may give rise to subthreshold production of light hadrons and charm.

\footnote{Talk given at the meeting on \textit{Future Electron Accelerators and Free Electron Lasers}, Uppsala, April 25-26, 1996. Work supported in part by the EU/TMR contract ERB FMRX-CT96-0008.}
1 Introduction

The ELFE@DESY project aims at utilizing a future DESY linear electron collider \[1\] to accelerate electrons to 15…30 GeV and then use the HERA electron ring to stretch the collider bunches into an intense (30 µA) continuous extracted beam \[2\]. Polarized electrons will be scattered from both light and heavy fixed targets, with luminosities in the \( \mathcal{L} = 10^{35} \ldots 10^{38} \text{ cm}^{-2}\text{s}^{-1} \) range. In this talk I discuss some of the central physics issues that can be addressed with this type of accelerator. Since ELFE experiments are many years in the future I shall concentrate on questions related to basic aspects of QCD, which will remain of fundamental interest and which require the capabilities of an accelerator like ELFE.

Table 1. Features and opportunities of an ELFE accelerator.

| Features                  | Opportunities                      |
|----------------------------|------------------------------------|
| High luminosity           | Study rare configurations          |
| \( \mathcal{L} \sim 10^{35} \ldots 10^{38} \text{ cm}^{-2}\text{s}^{-1} \) | of target wave function            |
| Energy                    | Perturbative QCD                   |
| \( E = 15 \ldots 30 \text{ GeV} \)  | Resolution of \( \mathcal{O}(0.1 \text{ fm}) \) |
|                            | Charm production                   |
| High duty factor \( \sim 80\% \) | Event reconstruction              |
| High energy resolution    | Exclusive reactions                |
| \( \Delta E/E \sim 5 \cdot 10^{-4} \)  | Inclusive reactions at high \( x \) |
| Polarization              | Amplitude reconstruction           |
|                            | Spin systematics of QCD            |

In Table 1 I list the main features of the ELFE accelerator, and the opportunities that they provide. Compared to existing electron and muon beams, the advantages of ELFE are in luminosity (compared to the muon beams at CERN and Fermilab), in duty factor (compared to SLAC) and in energy (compared to TJNAF). Competitive ELFE experiments will rely on a combination of these strong features. The HERMES experiment at DESY works in the same energy range but at a lower luminosity and duty factor compared to ELFE. HERMES will prepare the ground for ELFE physics, together with experiments at TJNAF in the U.S., GRAAL in Grenoble and the lower energy electron facilities ELSA (Bonn) and MAMI (Mainz).
As I shall discuss below, an important part of physics at ELFE will deal with exclusive reactions, or with inclusive reactions at large values of Bjorken

\[ x = Q^2/2mv. \]

The energy range of 15...30 GeV is actually optimal for such studies, as seen from the following argument. The inclusive deep inelastic cross-section scales (up to logarithmic terms) in the virtuality \( Q^2 \) and energy \( \nu \) of the photon like

\[
\frac{d^2\sigma_{DIS}}{dQ^2dx} \propto \frac{1}{Q^4} F(x)
\]

ExCLUSIVE processes are still more strongly suppressed at large \( Q^2 \), e.g.,

\[
\frac{d\sigma}{dQ^2(ep \rightarrow ep)} \propto \frac{F_p^2(Q^2)}{Q^4} \propto \frac{1}{Q^{12}} \quad (x = 1)
\]

Typically we want to reach at least \( Q^2 = \mathcal{O}(10 \text{ GeV}^2) \) to be able to use perturbative QCD (PQCD) and to have a resolution of \( \mathcal{O}(0.1 \text{ fm}) \). This implies \( \nu = \mathcal{O}(5 \text{ GeV}) \) at large \( x \simeq 1 \). At ELFE, such energies correspond to the photon taking a moderate fraction \( y = \nu/E_e \simeq 0.15...0.3 \) of the electron energy, which is practical for measurements. This may be contrasted with the situation at HERA, which is equivalent to a fixed target experiment with an electron energy \( E_e \simeq 50000 \text{ GeV} \). A photon with energy \( \nu = 5 \text{ GeV} \) would at HERA correspond to \( y \simeq 0.0001 \). It is clearly very difficult to measure the large \( x \), moderate \( Q^2 \) region at HERA, but it is the natural territory of an accelerator in the ELFE energy range.

In the following I shall discuss three aspects of physics at ELFE which relate to basic issues in QCD:

- **Wave function measurements.** Most of our present knowledge of hadron and nuclear wave functions stems from hard inclusive scattering, which measures single parton distributions. The phenomenology of hard exclusive scattering, which is sensitive to compact valence quark configurations, is still in its infancy. Although considerable progress may be expected in this field in the coming years, the measurements are so demanding that an accelerator with ELFE’s capabilities is sorely needed. On the theoretical front, we still do not have a full understanding of which properties of the wave function are in principle measurable in hard scattering. It seems plausible that semi-inclusive processes can be used to measure configurations where a subset of partons are in a compact configuration, while the others are summed over.

- **Short range correlations in nuclei.** Scattering which is kinematically forbidden for free nucleon targets has been experimentally observed, and includes DIS at \( x > 1 \), hadron production at Feynman \( x_F > 1 \) and subthreshold production processes. Such scattering requires short range correlations between partons in more than one nucleon, and thus gives information about unusual, highly excited nuclear configurations.
• **Charm production near threshold.** Production close to threshold requires efficient use of the target energy and hence favors compact target configurations. Heavy quarks are created in a restricted region of space-time, where perturbative calculations are reliable. Both features conspire to make the production of charm near threshold a sensitive measure of new physics, including unusual target configurations and higher twist contributions. The ELFE accelerator will work in the region of charm threshold ($E_\gamma \simeq 9$ GeV) and provide detailed information about both charmonium and open charm production.

The above selection of physics topics is obviously far from complete. I refer to earlier presentations of ELFE physics [4] as well as to the review by Brodsky [5] for further discussions of these and other aspects of QCD phenomenology. In particular, I shall not cover here the important and topical area of color transparency, but refer to recent reviews [6] and references therein.

## 2 Wave function measurements

### 2.1 Inclusive Deep Inelastic Scattering

Our most precise knowledge of nucleon (and nuclear) structure is based on deep inelastic lepton scattering (DIS), $\ell N \rightarrow \ell' X$, and related hard inclusive reactions. As is well-known, DIS measures the product of a parton-level subprocess cross-section $\hat{\sigma}$ and a target structure function $F$. Thus, schematically and at lowest order in the strong coupling $\alpha_s$,

$$ \frac{d^2\sigma(eN \rightarrow eX)}{dQ^2 dx} = \hat{\sigma}(eq \rightarrow eq) F_{q/N}(x, Q^2) [1 + \mathcal{O}(\alpha_s)] $$

(3)

The structure functions $F_{q/N}$ have been measured over an impressive range in $x$ and $Q^2$, covering $0.0001 \lesssim x \lesssim 1$ and $1 \lesssim Q^2 \lesssim 10000$ GeV$^2$. Their logarithmic $Q^2$-dependence (‘scaling violations’) predicted by QCD has been tested, and their ‘universality’ verified, i.e., the same structure functions describe other hard inclusive reactions such as $pp \rightarrow jet + X$, $\pi^- p \rightarrow \mu^+\mu^- + X$, $pp \rightarrow \gamma + X$, etc. The many detailed measurements and successful cross-checks have together established QCD as the correct theory of the strong interactions, and made us confident that basic properties of hadron wave functions can be deduced from experimental measurements using the methods of PQCD.

The success of DIS phenomenology should not make us forget that the structure function $F_{q/N}(x, Q^2)$, no matter how completely known, still only provides

1Due to space limitations, this topic is not included in these proceedings, but will be published separately [3].
us with a very limited knowledge of the nucleon wave function. In terms of a
(light-cone) Fock state expansion of the proton wave function,

\[ |p\rangle = \int \prod_i dx_i d^2 k_{\perp i} \{ \Psi_{uud}(x_i, k_{\perp i})|uud\} + \Psi_{uudg}(\ldots)|uudg\rangle + \ldots \] (4)

the structure function \( F_{q/p} \) can be expressed as a sum over the absolute squares of all Fock components \( n \) that contain a parton \( q \) with the measured momentum fraction \( x \),

\[ F_{q/p}(x, Q^2) = \sum_n \int \prod_i k_{\perp i} \frac{d^2 k_{\perp i}}{Q^2} |\Psi_n(x_i, k_{\perp i})|^2 \delta(x - x_q) \] (5)

Due to the average over Fock states, the most probable states will typically dominate in the structure function. Information about partons which do not participate in the hard scattering is lost in the sum of Eq. (5). The structure function is a single parton inclusive probability distribution that does not teach us about parton correlations. However, at large values of \( x \) the structure function singles out unusual Fock states where one parton carries nearly all momentum, and all other partons therefore must have low \( x \).

### 2.2 Hard Exclusive Scattering

Clearly, it is desirable to make also other measurements of hadron wave functions. This is not as easy as it sounds, given that we only master the perturbative region of QCD. We need to study a hard scattering, where the subprocess can be identified and calculated, and where the dependence on the soft wave function factorizes. The factorization between hard and soft processes is a nontrivial feature in a theory like QCD with massless (long-range) gluon exchange. Even in inclusive scattering factorization has only been proved for a subset of the measurable hard processes [7].

The hard subprocess can occur coherently off several partons if the distance between them is commensurate with the momentum transfer \( Q \). Such (‘higher twist’) processes are more strongly damped in momentum transfer than DIS (cf Eqs. (1) and (2)), since the partons must be increasingly close as \( Q \) grows. This is what happens in hard exclusive processes, where factorization is also expected to apply [8]. As an example, consider elastic electron-proton scattering, \( ep \rightarrow ep \) at large momentum transfer \( Q \) (Fig. 1a). The amplitude for this process has been shown to factorize into a product of a hard scattering part \( T_H \) and proton ‘distribution amplitudes’ \( \varphi_p \),

\[ A(ep \rightarrow ep) = \int_0^1 \prod_i^3 dx_i dy_i \varphi_p(x_i, Q^2) T_H \varphi_p(y_i, Q^2) \{1 + O(1/Q^2)\} \] (6)
Figure 1: a. Elastic $ep \to ep$ scattering at large $Q^2$ factorizes into a product of proton distribution amplitudes $\varphi_p$ and a hard electron scattering from the compact valence Fock state $|uud\rangle$. b. An analogous factorization is illustrated for the large angle process $\pi^- p \to \pi^0 n$.

The proton distribution amplitude is the valence part of the Fock expansion, integrated over relative transverse momenta up to $Q$,

$$\varphi_p(x_i, Q^2) = \int k_{i\perp}^2 < Q^2 \prod_i d^2 \vec{k}_{i\perp} \Psi_{uud}(x_i, k_{i\perp})$$

where the $x_i$ denote the longitudinal momentum fractions of the valence $uud$ constituents. The integral over the relative transverse momenta $k_{i\perp}$ implies that the transverse size of the valence state is $r_{\perp} \approx 1/Q$. The hard amplitude $T_H$ describes the subprocess $e + (uud) \to e + (uud)$, which selects compact $|uud\rangle$ states.

The logarithmic $Q^2$ dependence of the proton distribution amplitude is given by

$$\varphi_p(x_i, Q^2) = 120 x_1 x_2 x_3 \delta(1 - x_1 - x_2 - x_3) \sum_{n=0} \left[ \frac{\alpha_s(Q^2)}{\alpha_s(Q_0^2)} \right]^{\lambda_n} C_n P_n(x_i)$$

The anomalous dimensions form an increasing series

$$\lambda_0 = \frac{2}{27} < \lambda_1 = \frac{20}{81} < \lambda_2 = \frac{24}{81} < \ldots$$

implying that each successive term in Eq. (8) decreases faster with $Q^2$ than the previous one. The $P_n$ are Appell polynomials, $P_0 = 1, P_1 = x_1 - x_3, P_2 = 1 - 3x_2, \ldots$ and the $C_n$ are constants which characterize the proton wave function and
have to be determined from experiment. The \( Q^2 \) evolution of the pion distribution amplitude is given by an expression similar to Eq. (8). The overall normalization of the pion distribution amplitude is fixed by the decay constant \( f_\pi \) measured in \( \pi \rightarrow \mu \nu \) decay.

Just as in the case of inclusive scattering, the relevance of factorization for data on exclusive reactions must be demonstrated by showing that the same (universal) distribution amplitudes \( \varphi_h \) describe several hard exclusive processes. For example, large angle \( \pi^- p \rightarrow \pi^0 n \) scattering should be described by the diagram of Fig. 1b, which involves the pion and proton distribution amplitudes and the \((q\bar{q}) + (qqq)\) elastic subprocess. Heavy meson decays like \( B \rightarrow \pi \pi \) can also be analyzed in the same formalism (assuming that the momentum transfers involved are large enough).

Tests of factorization in exclusive reactions are quite difficult in practice. From a theoretical point of view, the calculation of multi-parton scattering amplitudes like those in Fig. 1 are very demanding even at the Born level, due to the large number of Feynman diagrams. It is also difficult to estimate how high momentum transfers are required in order to reach the scaling regime. Thus in Fig. 1a the momentum transfer \( Q \) from the electron is effectively split among the three quarks of the proton. The less momentum a quark carries, the less transfer it needs to scatter to a large angle. There is an especially dangerous region where some of the valence quarks carry a very small fraction \( x \) of the proton momentum, in which case they can fit into the proton wave function both before and after the hard scattering, without receiving any momentum transfer. There has been much discussion as to the importance of this ‘Feynman mechanism’ [9]. The consensus appears to be that it is suppressed asymptotically [10] due to the Sudakov effect [11]: The single quark carrying all the momentum cannot be deflected to a large angle without gluon emission. At finite (and relevant) energies, the importance of the Feynman mechanism is still not settled – and its significance may depend on the reaction.

An immediate consequence of factorization for exclusive reactions is the ‘counting’ or ‘dimensional scaling’ rule [12], which gives the power of the squared momentum transfer \( t \) by which any \( 2 \rightarrow 2 \) fixed angle differential cross section is suppressed (up to logarithms),

\[
\frac{d\sigma}{dt}(2 \rightarrow 2) \propto \frac{f(t/s)}{t^{n-2}}
\]

where \( n \) is the total number of elementary fields (quarks, gluons, photons) that are involved in the scattering. This rule follows from simple geometrical considerations. Elastic scattering between two elementary fields (eg, \( q\bar{q} \rightarrow q\bar{q} \)) involves no dimensionful quantities except \( s \) and \( t \) and thus obeys Eq. (10) with \( n = 4 \) at fixed \( t/s \). Each additional field that is involved in the scattering must be within a transverse distance of order \( r_\perp \lesssim 1/Q \) (with \( Q^2 = -t \)) to scatter coherently, and the probability for that is of \( \mathcal{O}(1/(Q^2 R^2)) \), where \( R \simeq 1 \text{ fm} \) is the average
radius of the hadron. This rule also explains why the dominant contribution to hard scattering comes from the valence Fock states, which minimize the power $n$ in Eq. (10).

It is encouraging (although by no means conclusive) for factorization in hard exclusive processes that the scaling rule (10) is approximately obeyed by the data for many reactions. Thus, $ep \rightarrow ep$ involves a minimum of $n = 8$ fields, implying that the proton form factor should scale as $F_p(Q^2) \propto 1/Q^4$, as assumed in Eq. (2). Data is available [13] for $Q^2 < 30$ GeV$^2$ and is consistent with this behavior for $Q^2 > 5$ GeV$^2$. At the higher values of $Q^2$ there are indications of scaling violations that are consistent with the logarithmic evolution predicted by Eq. (6).

Tests of the dimensional scaling rules in exclusive reactions are analogous to tests of Bjorken scaling in DIS, i.e., that the $Q^2$ dependence of the inclusive cross section is given by Eq. (1). In DIS, the cross section as a function of $x$ then directly measures the structure function $F(x)$. In exclusive reactions the situation is not as favorable. The experimentally determined normalization of the proton form factor only gives us one number, which is an average of the proton distribution amplitude integrated over the momentum fractions $x_i$ carried by the valence quarks. To make a quantitative prediction one must know both the shape and the normalization of the (non-perturbative) distribution amplitude. The good news is that the asymptotic form of the amplitude in the $Q^2 \rightarrow \infty$ limit is known, $\varphi_{p}^{AS} \propto x_1 x_2 x_3$ according to Eq. (8). The non-asymptotic corrections are encoded in the moments $C_i$ which are measurable in principle. Considerable efforts have been made to determine the pion and proton distribution amplitudes theoretically using lattice calculations and QCD sum rules [14, 15].

One of the simplest hard exclusive processes is the pion transition form factor $F_{\pi\gamma}(Q)$, measured by the process $e\gamma \rightarrow e\pi$ at large momentum transfer $Q$, cf Fig. 2a. The existing data [16] in the range $1 < Q^2 < 8$ GeV$^2$ shown in Fig. 2b is well fit using a pion distribution amplitude close to the asymptotic form $\varphi_{\pi}^{AS} \propto x_1 x_2$ [17]. Considering that the absolute normalization in the large $Q^2$ limit is fixed by the pion decay constant, $F_{\pi\gamma}^{AS} = \sqrt{2} f_{\pi}/Q^2$, the agreement is very encouraging and indicates that the factorization formalism applies even at moderate values of $Q^2$. There is evidence, on the other hand, that the asymptotic regime may be more distant in the case of the pion form factor measured by $e\pi \rightarrow e\pi$ large angle scattering [18].

There are many other processes that can and need to be analyzed experimentally and theoretically in order to achieve a comprehensive understanding of the phenomenology of hard exclusive scattering. A particularly important process is virtual compton scattering $\gamma^* p \rightarrow \gamma p$, which involves no hadrons except the proton and offers the possibility of varying independently both the virtuality of the photon and the momentum transfer to the proton [19, 20, 13, 21]. Many exclusive processes involve resonance production and thus require the measurement of multiparticle final states. It seems clear that the phenomenology of rare
Figure 2: a. The pion transition form factor $F_{\pi\gamma}$ is measured by the process $e\gamma \rightarrow e\pi$, and factorizes at high $Q^2$ into a product of the calculable hard subprocess $e\gamma \rightarrow e + (q\bar{q})$ and the pion distribution amplitude $\varphi_\pi$. b. Data [10] compared with calculations based on a pion distribution amplitude close to the asymptotic one (solid line) and one based on QCD sum rules [14] (dashed line). The dotted line represents the asymptotic result $\sqrt{2}f_\pi$. Figure from Kroll et al. in [17].

exclusive processes requires the capability of an ELFE type accelerator, which combines sufficient energy with high luminosity in a continuous electron beam.

2.3 Scattering from Compact Subsystems

Both in inclusive DIS and in hard exclusive processes a photon (or gluon) scatters from a parton system ($q, g, q\bar{q}$ or $qqq$) with a transverse size of $O(1/Q)$, compatible with the photon wavelength. Intuitively, this is required for the physics of the hard perturbative scattering to factorize from the non-perturbative wave function, which determines the probability for such compact systems.

Fully inclusive scattering like DIS measures single parton distributions, with no constraint on the size of the Fock state to which they belong. In exclusive scattering the whole Fock state is required to be compact. There are also intermediate (semi-inclusive) hard processes where the scattering occurs off multiparton subsystems of the hadron, such as $qq$, $gg$, etc. The theoretical framework for such processes is still incomplete, but the factorization of hard and soft physics seems plausible. This would allow experimental measurements of the compact subsystems and of the momentum fraction that they carry.

As an example, consider the semi-inclusive process $ep \rightarrow e\pi + X$ sketched in
Fig. 3a, where the pion takes a fraction $z$ of the photon energy $\nu$. In the limit $z \to 1$ the photon transfers all its energy to the pion, which selects compact $q\bar{q}$ configurations \cite{22,23}. Alternatively (and in fact equivalently), the struck quark needs to combine with a very soft antiquark to form the pion – such asymmetric configurations are short-lived and indistinguishable (by the photon) from compact $q\bar{q}$ pairs \cite{24}. Thus the cross section can be expected to factorize in the $z \to 1$ limit as

$$\sigma = \hat{\sigma}(e + (q\bar{q}) \to e + (q\bar{q})) F_{q\bar{q}/p}(x) |\phi_\pi|^2$$

(11)

where $F_{q\bar{q}/p}(x)$ is the probability for finding the compact quark pair in the target, and the pion distribution amplitude $\phi_\pi$ is the amplitude for the pair to transform into a physical pion.

![Diagram](image)

Figure 3: a. Electron scattering off compact $q\bar{q}$ pairs in the target are selected by the semi-inclusive process $ep \to e\pi + X$ when the pion carries a large fraction $z$ of the photon energy. b. Model calculation \cite{23} of the ratio $\sigma_L/(\sigma_L + \sigma_T)$, showing how coherent scattering on $q\bar{q}$ begins to dominate at large $z$. The curves correspond to different choices of the pion distribution amplitude.

Scattering off $q\bar{q}$ pairs (having integer spin) can be distinguished from scattering off single (spin 1/2) quarks through the ratio $\sigma_L/(\sigma_L + \sigma_T)$ of the longitudinally polarized to total photon cross sections. As is well known, $\sigma_L = 0$ (up to higher order QCD corrections) for scattering from spin 1/2 quarks, whereas $\sigma_T = 0$ for scattering on spin 0 diquarks. A calculation of the cross section ratio as a function of $z$ based on the model orginally proposed in Ref. \cite{22} is shown in Fig. 3b. Experimental evidence for an analogous effect has been seen in the
reverse reaction $\pi N \rightarrow \mu^+\mu^- + X$, where the muon pair takes a high fraction $x_F$ of the pion momentum $[24]$.

Systematic high statistics studies of semi-inclusive reactions for several targets will allow measurements of both the diquark structure function $F_{q\bar{q}/p}(x)$ in Eq. (11) and of nuclear effects on the pion distribution amplitude $\varphi_\pi$, due to incomplete color transparency. A precise theoretical formulation of scattering from subsystems is called for and progress in this direction is being made $[15, 21, 26]$. 

3 Short Range Correlations in Nuclei

The inclusive nuclear structure function is to a first approximation given by the nucleon one, $F_{q/A}(x) \simeq AF_{q/N}(x) [27]$. Deviations of $O(20\ldots 30\%)$ are observed for small values of $x$ (‘shadowing’) and for $x = 0.5\ldots 0.7$ (the ‘EMC effect’). When viewed in coordinate space, one finds $[28]$ that the quark ‘mobility distribution’ is almost independent (at the 2% level) of $A$ up to light-cone distances (conjugate to $Q^2/2\nu$) of order 2 fm, with shadowing setting in at larger distances. Since DIS (at moderate $x$ and in coordinate space) is dominated by the most common Fock states, this result shows that typical nucleon configurations are little affected by the nuclear environment. The shadowing effect at large light-cone distances reflects coherent scattering off several nucleons in the nucleus.

In contrast to inclusive scattering, hard semi-inclusive and exclusive scattering select rare parton configurations, where some or all of the partons in the Fock state are at short relative transverse distance. Since such configurations do not contribute to DIS at moderate values of $x$ their $A$-dependence is essentially unknown. Clusters that carry more momentum than single nucleons in the nucleus are of special interest, since they select nuclear configurations where several nucleons are at short relative distance. In the parlance of nuclear physics, these represent highly excited states of the nucleus (with excitation energies in the GeV region) about which we know very little at present. An electron beam of high intensity and resolution is essential for mapping out such dense clusters.

In DIS on nuclei, the fraction $x = Q^2/2m_p\nu$ of the target momentum carried by the struck quark has the range $0 \leq x < A$. Data at $x \cong 1$ exists and is difficult to explain by standard Fermi motion $[29, 30, 31]$. Models based on short-range correlations between nucleons $[32]$ and on multi-quark effects $[33]$ can fit the data, but considerably more experimental and theoretical effort will be needed to clarify the physics of this ‘cumulative’ region of nuclei.

Novel cumulative effects are observed also in nuclear fragmentation into hadrons $[32, 34, 35]$. The hadron ($p$, $\pi$, $K$) momentum distributions extend beyond $x_F = 1$, i.e., their momentum must have been transferred from several nucleons. The fragmentation is only weakly dependent on the nature of the projectile or its energy, indicating that it measures features intrinsic to the nuclear wave function. In these processes the projectile scattering is soft, but there is evidence $[36]$
that the average transverse momentum of the produced hadrons increases with \( x_F \), reaching \( \langle p_T^2 \rangle = 2 \text{ GeV}^2 \) at \( x_F = 4 \) for protons. The cumulative momentum transfers thus appear to originate in a transversally compact region of the nucleus.

Cumulative nuclear effects have furthermore been observed in subthreshold production of antiprotons and kaons \([37]\). The minimal projectile energy required for the process \( pp \to \bar{p} + X \) on free protons at rest is 6.6 GeV. The kinematic limit for \( pA \to \bar{p} + X \) on a heavy nucleus at rest is only \( 3m_N \simeq 2.8 \text{ GeV} \). This reaction has been observed for \( A = ^{63}\text{Cu} \) down to \( E_{\text{lab}} \simeq 3 \text{ GeV} \), very close to kinematic threshold. Scattering on a single nucleon in the nucleus would at this energy require a Fermi momentum of \( \mathcal{O}(800) \text{ MeV} \). While the \( pA \) data can be fit assuming such high Fermi momenta, this assumption leads to an underestimate of subthreshold production in \( AA \) collisions by about three orders of magnitude \([38]\).

It is possible that the subthreshold production of \( K \) and \( \bar{p} \) on nuclei involves the same compact multiparton clusters that are responsible for scattering with \( x > 1 \) and \( x_F > 1 \), although this is far from clear at present. A study of subthreshold production using lepton beams could be quite informative, since the locality of the reaction can be tuned through the virtuality of the exchanged photon. A further possibility to pin down the reaction mechanism is provided by subthreshold production of charm. ELFE will in fact be working close to charm threshold, allowing for many interesting phenomena. A discussion of charm physics near threshold can be found in Ref. \([3]\).

### 4 Conclusions

There are (at least) three central physics areas which require an accelerator with the capabilities of ELFE as given in Table 1:

- The determination of hadron and nuclear wave functions.
- Specifically nuclear effects: Color transparency \([6]\), cumulative phenomena \([29] - [38]\).
- Charm(onium) production near threshold \([3]\).

In addition to these core topics there are a number of areas where ELFE can improve on presently available data, such as

- The nucleon structure function for \( 0.7 \lesssim x \lesssim 1 \),
- Higher twist corrections of the form \( c(x)/Q^2 \),
- \( R = \sigma_L/\sigma_T \),
– The gluon structure function,

– Polarized structure functions.

Significant advances in these areas are, however, expected from other experiments before ELFE starts operating.

Finally, we should keep in mind that the whole area of ‘confinement’ physics is very important but at present poorly understood in QCD. It includes open questions like the influence of the QCD vacuum on scattering processes \[39\] and the foundations of the non-relativistic quark model (see, eg, \[40, 41\]). It is difficult to assess today what the progress will be in this field. Nevertheless, it seems clear that systematic measurements of non-perturbative wave functions as discussed above will form an essential part of any serious effort to understand the hadron spectrum.

Acknowledgements. I would like to thank the organizers of this meeting for arranging a very interesting cross-disciplinary discussion of the research possibilities at a future DESY linear collider. My understanding of the material discussed above stems mainly from a long and fruitful collaboration with Stan Brodsky. I am also grateful for helpful discussions with V. M. Braun and M. Strikman.

References

[1] B. H. Wiik, *Future Electron Accelerators and Free Electron Lasers*, Talk given at this meeting.

[2] B. Frois, *Nuclear Physics – Experimental Aspects*, Talk given at this meeting; A. Tkatchenko, *Machine Project for ELFE at DESY*, Talk given at the Second ELFE Workshop, St. Malo, 22-27 September 1996.

[3] P. Hoyer, *Charmonium Production at ELFE Energies*, talk at the 2nd ELFE Workshop, Saint Malo, France, Sept. 1996 (to be published).

[4] B. Frois and B. Pire, Invited talk at 8th International Nuclear Physics Conference (INPC 95), Beijing, P.R. China, 21-26 Aug 1995, hep-ph/9512221; J. Arvieux and B. Pire, Prog. Part. Nucl. Phys. 35 (1995) 299.

[5] S. J. Brodsky, Talk presented at Orbis Scientiae (Miami Beach 1996), SLAC-PUB-7152, hep-ph/9604391.

[6] N. N. Nikolaev and B. G. Zakharov, Talk at the INPC Conference, Beijing, China, August 1995, KFA-IKP(TH)-1995-21, nucl-th/9509036; P. Hoyer, Talk at Workshop on Deep Inelastic Scattering and QCD (DIS 95), Paris, France, April 1995, proceedings Paris DIS 1995:127, hep-ph/9510394.
[7] J. C. Collins, D. E. Soper and G. Sterman, in *Perturbative QCD*, ed. A. H. Mueller (World Scientific, 1989); G. Bodwin, Phys. Rev. D31 (1985) 2616 and D34 (1986) 3932 (E); J. Qiu and G. Sterman, Nucl. Phys. B353 (1991) 105 and B353 (1991) 137.

[8] For a review, see S. J. Brodsky and G. P. Lepage in *Perturbative QCD*, edited by A. H. Mueller (World Scientific, Singapore, 1989).

[9] N. Isgur and C. H. Llewellyn-Smith, Nucl. Phys. B317 (1989) 526; A. V. Radyushkin, Nucl. Phys. A532 (1991) 141c.

[10] J. Botts and G. Sterman, Nucl. Phys. B325 (1989) 62.

[11] V. V. Sudakov, Sov. Phys. JETP 3 (1956) 65.

[12] S. J. Brodsky and G. R. Farrar, Phys. Rev. Lett. 31 (1973) 1153; V. A. Matveev, R. M. Muradyan and A. V. Tavkhelidze, Lett. Nuovo Cimento 7 (1973) 719.

[13] A. F. Sill *et al.*, Phys. Rev. D28 (1993) 860.

[14] V. L. Chernyak and A. R. Zhitnitsky, Phys. Rep. 112 (1984) 173; S. V Mikhailov and A. V. Radyushkin, Phys. Rev. D45 (1992) 1754; A. V. Radyushkin and R. Ruskov, Phys. Lett. B374 (1996) 173.

[15] A. V. Radyushkin, Talk at Workshop on Virtual Compton Scattering, Clermont-Ferrand, France, June 1996, JLAB-THY-96-06, hep-ph/9609387.

[16] CELLO Collaboration, H.-J. Behrend *et al.*, Z. Phys. C49 (1991) 401; CLEO Collaboration, V. Savinov *et al.*, proceedings of the PHOTON ’95 Workshop Sheffield, England, April 1995, hep-ex/9507005.

[17] A. V. Radyushkin and R. Ruskov, CEBAF-TH-95-18, hep-ph/9603408; P. Kroll and M. Raulfs, Phys. Lett. B387 (1996) 848, hep-ph/9605264.

[18] R. Jakob and P. Kroll, Phys. Lett. B315 (1993) 463; B319 (1993) 545 (E).

[19] M. A. Shupe *et al.*, Phys. Rev. D19 (1979) 1929.

[20] A. S. Kronfeld and B. Nižić, Phys. Rev. D44 (1991) 3445; G. R. Farrar, K. Huleihel and H. Zhang, Nucl. Phys. B349 (1991) 655.

[21] X. Ji, MIT-CTP-2568, hep-ph/9609381.

[22] E. L. Berger and S. J. Brodsky, Phys. Rev. Lett. 42 (1979) 940; A. Brandenburg, S. J. Brodsky V. V. Khoze and D. Muller, Phys. Rev. Lett. 73 (1994) 939, hep-ph/9403361; K. J. Eskola, P. Hoyer, M. Vänttinen and R. Vogt, Phys. Lett. B333 (1994) 526, hep-ph/9404322.
[23] A. Brandenburg, V. V. Khoze and D. Muller, Phys. Lett. B347 (1995) 413, hep-ph/9410327.

[24] S. J. Brodsky, P. Hoyer, A. H. Mueller and W.-K. Tang, Nucl. Phys. B369 (1992) 519.

[25] E615 Collaboration, J. S. Conway et al., Phys. Rev. D39 (1989) 92.

[26] X. Ji, MIT-CTP-2517, hep-ph/9603249; A. V. Radyushkin, CEBAF-TH-96-06, hep-ph/9605431.

[27] M. Arneodo, Phys. Rep. 240 (1994) 301.

[28] P. Hoyer and M. Vänttinen, NORDITA-96-20-P, hep-ph/9604305.

[29] BCDMS Collaboration, A. C. Benvenuti et al., Z. Phys. C63 (1994) 29.

[30] J. Arrington et al., Phys. Rev. C53 (1996) 2248.

[31] CCFR/NuTeV Collaboration, M. Vakili et al., in Proceedings of the Division of Particles and Fields meeting, 1996 (DPF96), Minneapolis, USA, August, 1996.

[32] L. L. Frankfurt and M. Strikman, Phys. Rep. 160 (1988) 325; L. L. Frankfurt, M. I. Strikman, D. B. Day and M. Sargsyan, Phys. Rev. C48 (1993) 2451.

[33] A. V. Efremov, Sov. J. Part. Nucl. 13 (1982) 254; L. Kaptari and A. Umnikov, JINR Rapid Commun. 32 (1988) 17; S. Gupta and R. M. Godbole, Phys. Lett. 228B (1989) 129.

[34] V. S. Stavinskii, Sov. J. Part. Nucl. 10 (1979) 373.

[35] J. V. Geagea et al., Phys. Rev. Lett. 45 (1993) 1980; A. Gillitzer et al., Z. Phys. A354 (1996) 3.

[36] S. V. Boyarinov et al., Sov. J. Nucl. Phys. 46 (1987) 871.

[37] J. B. Carroll et al., Phys. Rev. Lett. 62 (1989) 1829; A. Shor et al., Phys. Rev. Lett. 63 (1989) 2192; A. Schröter et al., Z. Phys. A350 (1994) 101.

[38] A. Shor, V. Perez-Mendez and K. Ganezer, Nucl. Phys. A514 (1990) 717.

[39] O. Nachtmann, Johns Hopkins Workshop 1994:143-172, hep-ph/9411345.

[40] D. Diakonov, Talk at International School of Nuclear Physics, Erice, Italy, Sept. 1995, nucl-th/9603023.

[41] P. Hoyer, NORDITA-96/63 P, hep-ph/9610270.