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The ELFE Project, an Electron Accelerator for Europe *

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1 Introduction

The name "ELFE" stands for Electron Laboratory For Europe, a 15 – 30 GeV electron accelerator with a high duty cycle of 80% – 100% and high intensity 10 – 50 μA. The nuclear physics community has developed an increasing interest in high energy physics experiments which push the frontier of microscopic understanding of the nucleus to smaller and smaller distances. In the United States CEBAF accelerated its first beam with electrons of several GeV. Above 30 GeV electron or muon beams at SLAC, CERN, FERMILAB and HERA have been excellent microscopes to see quarks and gluons in the nucleon. Is there a possible niche inbetween, where new and fundamental discoveries in a European laboratory can be made ? This question has been debated intensely. A documentation of the ideas leading to ELFE can be found in several conference proceedings [1]. Earlier this year the ELFE project has been submitted to the Nuclear Physics European Collaboration Committee (NuPECC) for evaluation. Currently there are two activities around ELFE. One is a technological effort to develop superconducting cavities for high intensity beams. The other activity is to build up a European network [2] developing the physics which can be studied with such a machine. I will try in this short contribution to give my view of the physics case for ELFE.

Electron-hadron scattering can be seen as the scattering of a virtual photon with energy $\nu = E_i(e) - E_f(e)$ and negative four momentum square

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$-q^2 = Q^2 = 4E_i(e)E_f(e)\sin^2\theta$ where θ is the scattering angle of the electron in the laboratory. For large Q^2 and ν the Bjorken scaling variable $x = Q^2/2m\nu$ or the inclusive mass of the hadronic final state $W^2 = (p+q)^2 = m^2 + Q^2(\frac{1}{x} - 1)$ are useful variables.

High energy electron scattering at varying resolution measures parton momentum distributions N_q. At high Q^2 these distribution functions scale, i.e. they depend on the momentum fraction $x = Q^2/2m\nu$ of the struck quark with respect to the proton momentum in the cm frame. The weak logarithmic $ln\ Q^2$ dependence of the structure functions $F_2(x, Q^2)$ for $Q^2 > 10\ GeV^2$ is a direct consequence of asymptotic freedom, i.e. weakly interacting quarks and gluons.

$$F_2(x, Q^2) = \sum_q x N_q(x, Q^2) e_q^2 \tag{1}$$

For low Q^2 e.g. at CEBAF, the physics varies strongly with Q^2, because of the existence of constituent quarks bound in hadrons. Concerning ELFE one has to answer the basic question: What physics can we learn at distance scales between the size of the constituent quark and the naked parton. Can an electron accelerator with varying resolution $0.5\ GeV^2 < Q^2 < 15\ GeV^2$ unravel the mystery of mass in hadronic physics? How do 10 MeV current quarks combine to form a 900 MeV proton? At low resolution Q^2, a Light Cone Schrödinger Equation for a $Q\bar{Q}$ bound state with constituent quark masses m_q

$$\left(\frac{p_\perp^2 + m_q^2}{x} + \frac{p_\perp^2 + m_q^2}{1-x} - M^2\right)\psi_{Q\bar{Q}}(x, p_\perp) =$$
$$\int dx' dp'_\perp < x, p_\perp | V_{LC} | x', p'_\perp > \psi_{Q\bar{Q}}(x', p'_\perp) \tag{2}$$

seems a natural starting point to describe the valence structure of the meson. In this equation M^2 is the meson mass squared i.e. the eigenvalue, which has to be solved. The light-cone potential energy operator [3] is not well understood theoretically. Especially it is not known how confinement and chiral symmetry breaking are to be included in V_{LC}. In exclusive electron scattering one can measure light-cone wave functions and thereby test solutions obtained from reasonable potentials. The structure function is related to the integral over the square of the wave function $N(x, Q^2) = \int^{Q^2} d^2p_\perp |\psi_{Q\bar{Q}}(x, p_\perp)|^2$. Twenty years after the discovery of QCD, there is no serious ab initio calculation of the structure functions of the pion or the nucleon. Measurements of relativistic hadron wave functions are a necessary first step to understand the bound state dynamics of QCD. The unique combination of high duty cycle $[80\% - 100\%]$ with high intensity $[(10 - 50)\mu A]$ at ELFE makes exclusive experiments e.g. on the π–or K-formfactors possible, as it will be discussed in the next section.

2 The Hadron Physics Program

2.1 Semi-inclusive meson production

A high duty cycle and high intensity machine like ELFE can explore coincidence experiments $e + p \rightarrow e' +$ meson (or baryon) $+X$. These experiments define a natural lower limit for the projected electron energy. In order to differentiate fragments from the struck quark and the target remnant, the two fragmentation regions have to be clearly separated. Since particles of a fragmenting object spread over a rapidity interval $\Delta y \approx 2$, a maximum rapidity width $Y_{max} = ln(Q^2(1 - x)/xm^2) \approx 4$ between the quark and proton remnant is necessary, therefore a 30 GeV energy seems to be well suited to seperate projectile and target fragmentation region.

Let us consider pion production in the following: Soft fragmentation for small $z = E_\pi/\nu$ is well measured and is used to parametrize the fragmentation functions $D_{\pi/q}(z, Q^2)$. Besides soft fragmentation we expect also other processes. The struck quark may recombine with the antiquark from a radiated hard gluon into a pion. This process is rather independent on z, but suppressed with Q^2. At very large z - the virtual photon may strip off a pion directly from the constituent quark. Therefore the semi-inclusive reaction can measure the intrinsic structure of the constituent quark, e.g. the momentum distribution of its pion cloud. A calculation [4] of the hard fragmentation (s-channel) and (t-channel) strip-off process clearly shows the increase of the cross-section near $z \to 1$.

2.2 Exclusive reactions

At $z = 1$ the pion production allows only a nucleon in the final state $e + p \to e + \pi^+ + n$. To measure the pion form factor $F_\pi(Q^2)$, one has to isolate the longitudinal semi-inclusive structure function H_L and extrapolate to small $t = (q_\gamma - k_\pi)^2$. The formfactor $F_\pi(Q^2)$ is given in terms of the light-cone wave function $\psi(x, p_\perp)$ as:

$$F_\pi(Q^2 = \vec{q}_\perp^{\,2}) = \int dx d^2 p_\perp \psi^*(x, \vec{p}_\perp) \psi(x, \vec{p}_\perp + (1-x)\vec{q}_\perp). \qquad (3)$$

Together with the constraints from the structure function, the pion decay constant f_π, the $\pi^o \to \gamma\gamma$ width and a measurement of $\gamma + \gamma^* \to \pi^o, F_\pi(Q^2)$ would severely constrain the light-cone wave funtion $\psi(x, \vec{p}_\perp)$. Recently there has been important progress [5] from perturbative QCD to understand the pion formfactor. The light-cone potential (eq.2) goes over into the one-gluon exchange potential at short distances. Therefore one can extract the asymptotic wave function from the light-cone Schrödinger equation. The QCD calculation reduces the measurement of $\psi(x, \vec{p}_\perp)$ to a small set of parameters describing its low $\vec{p}_\perp^{\,2}$ behaviour. In the ELFE energy region another very promising exclusive process is vector meson production $e + p \to e + (\rho, \omega, \phi, J/\psi) + p^*$. The wave function of the vector meson peaking at $x \approx 1/2$ selects a small $|Q\bar{Q}\rangle$ state. The $Q\bar{Q}$ admixture to the virtual photon at large $q_z = Q$ is approximately [6] given by

$$\Psi_{\gamma,\bar{Q}Q}(x_1, q_\perp) \approx e \cdot \frac{Q^2 x(1-x)}{Q^2 x(1-x) + q_\perp^2 + m_{Q^2}} \varphi_\gamma \tag{4}$$

with a size $r_\perp \approx \frac{2}{Q}$ This small size color dipole interacts with the proton via 2-gluon exchange. At low momentum transfer the gluon clouds of the different constituent quarks interfere, at large momentum transfer the gluon distribution of one quark enters and becomes measurable. Existing data on photo production of vector mesons stop rather early before this interesting high momentum transfer process sets it.

3 The Nuclear Physics Program

3.1 Color transparency and color neutralization

When the energy of the produced meson is large compared to its rest mass, the original $Q\bar{Q}$-state is frozen during its traversal of the nucleus. This way one can test the interaction of a small color dipole with the nucleus.

$$M_{\gamma N \to VN}(t=0) = \int dx \int d^2 r_\perp \bar{\Psi}_V(r_\perp, x) \Psi_{\gamma,\bar{Q}Q}(r_\perp, x) t^{VDW}(r_\perp) \tag{5}$$

The nucleons in the nucleus are color neutral, therefore the residual interaction is of the van der Waals type (VDW) with two gluon exchange cut-off at large distances

$$\begin{aligned} t^{VDW}(r_\perp) &= \sum_n \langle N|\vec{r}_\perp \vec{E}|n\rangle\langle n|\vec{r}_\perp \vec{E}|N\rangle \frac{1}{\Delta E_n} \\ &\approx \vec{r}_\perp^2 c\langle N|\vec{E}_\perp^2|N\rangle. \end{aligned} \tag{6}$$

One sees that small $Q\bar{Q}$-configurations selected by the x-integration ($x \approx 1/2$) at large Q^2 will be only weakly absorbed traversing the nucleus. This phenomenon has been called color-transparency. When the energy of the produced meson is diminished, the evolution of the $Q\bar{Q}$ state plays an important role. Both coherent exclusive processes and the transition to lower energies would be interesting reactions to be studied with nuclei at ELFE. In addition one sees that the color electric fluctuations $\langle N|\vec{E}^2|N\rangle$ in a nucleon in the nucleus enter. The gluon field strength distribution in the nucleus is still badly known, (J/ψ) production would be an important source of new information [7]. As has been shown in QED calculations [8], the weak binding of atoms in molecules is visible at extremely small x. I expect a similar feature for the nuclear binding. †

The discussion about the relative importance of gluonic and pionic degrees of freedom for nuclear binding can be made much more precise by measurements of the gluon and pion distributions in nuclei. The latter reaction $e + A \rightarrow e + \pi + X$ necessitates a careful investigation of color neutralization in the nucleus which can be done at ELFE.

3.2 Short Space Time Color Structure of the Nucleus

The study of the nucleus in terms of nucleons interacting via static potentials has been a challenging theoretical and experimental project. The intricacies of the NN-forces and the mesoscopic size of the nucleus (neither a few-body system nor a system of 10^{23} particles) generate a rich variety of nuclear physics phenomena, which is probably not yet exhausted. An electron microscope like ELFE with time resolution $1/\nu$ and space resolution $1/Q$ opens the view to see quark-gluon degrees of freedom of sizes $R \approx 0.1 - 0.3\ fm$ in a nucleus of almost 100 times bigger size. The EMC-effect has demonstrated the effect of nuclear binding on the structure function of the nucleon. A dedicated nuclear physics facility can study the nuclear structure function under extreme conditions of high nuclear density, when two nucleons are interacting at short distances by tagging on a high momentum backward

† To measure the gluon distribution at small x, the HERA accelerator as an electron-nucleus collider would be best.

nucleon $\gamma+(2N) \rightarrow N+X$. Especially dramatic nuclear effects are expected at $x > 1$. A high intensity, high duty factor machine allows to subtract the effects of quasi elastic nucleon knock out from deep inelastic scattering at high Q^2 and large x, where eventually scattering on genuine 6-quark clusters occurs.

4 Conclusions

A 30 GeV electron accelerator with high intensity and duty factor can supply detailed information about hadronic and nuclear structure at short distances. Relativistic light-cone wave functions of hadrons and the structure of their constituents become measurable in exclusive and semi-inclusive reactions. In the γ-nucleus interaction artificially small $(Q\bar{Q})$ components of the photon and tagged high density regions in the nucleus give new evidence for colored degrees of freedom and their interaction. Our current theoretical understanding of hadrons is far from precise. Experiments at ELFE will challenge us to develop a quantitative theory of QCD bound states in terms of weakly coupled constituent quarks with internal structure.

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