Physics with ELFE. *

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Abstract

A 15-30 GeV continuous beam electron facility has been proposed by nuclear physicists in Europe to study how color forces build up hadrons from quarks and gluons. This project and its physics case are briefly reviewed. The recommendations of NuPECC, the Nuclear Physics Committee of the European Science Foundation are presented.

1 Introduction

Recently, NuPECC, the Nuclear Physics Committee of the European Science Foundation (P. Kienle, Chairman) has recommended the construction of a 15-30 GeV high intensity continuous beam electron accelerator. The goal of this new facility is to explore the quark structure of matter by exclusive and semi-inclusive electron scattering from nuclear targets.

In the last two decades, we have seen the emergence of a theory that identifies the basic constituents of matter and describes the strong interaction [1]. The elementary building blocks of atomic nuclei are colored quarks and gluons. The theory describing their interactions is Quantum Chromodynamics (QCD) which has two special features, asymptotic freedom and color confinement. Asymptotic freedom means that color interactions are weak at short distances. Color confinement results in the

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existence of hadrons and in the impossibility to observe quarks and gluons as single particles. Color confinement and asymptotic freedom lead to the existence of two regimes. At short distances, quarks and gluons are in the regime of asymptotic freedom and behave in essence as free particles. At large distances, color interactions are strong and confine quarks and gluons in hadrons (mesons and baryons). A nucleus appears then to be built of nucleons interacting through the exchange of mesons.

Experimental results show that \textit{at the fermi scale} in the dense nuclear interior, nucleons keep their identity. Thus, a coherent description of nuclei at that scale has been achieved according to this concept of nuclei made of nucleons. At shorter distances, nucleons start to overlap and one must take their internal structure into account. Mesonic theory provides an efficient and economical description of nuclear reactions involving momentum transfers up to about 1 (GeV/c)^2, but for higher momentum transfers the situation becomes much more complex.

The limits of the description of nuclei in terms of nucleons and mesons are studied in Europe with the electrons accelerators of Amsterdam, Bonn and Mainz. We refer the reader to the reviews given at this conference by I. Sick, T. Walcher and P. de Witt Huberts. In the United States nuclear research with high energy electrons and photons is at present carried out at MIT-Bates accelerator. In the near future, this research will be focused at CEBAF, the 4 GeV continuous beam electron accelerator built at Newport News (Virginia) reviewed at this conference by F. Gross. This facility is nearly completed. The accelerator has just reached its nominal energy \( E = 4 \) GeV at the beginning of 1995. It will deliver simultaneously three beams on fixed targets. When CEBAF was designed, the design goal of superconducting cavities used for accelerating electrons was 5 MV/m. Since then, considerable progress has been achieved in the technology of superconducting cavities. The performances of the cavities delivered by industry exceed the expected performances in the original design of CEBAF. Instead of 4 GeV, the final energy of the continuous electron beam will be of the order of 6 GeV. There are already discussions to increase the energy of CEBAF to 8 GeV \[2\]. Beyond 12 GeV would require essentially to build a new facility.

Although one knows the microscopic theory for the strong interactions, \textit{one does not understand how quarks build up hadrons}.

After twenty years of theoretical developments we still lack reliable, analytic tools for this problem. This is one of the most important problem of contemporary physics. Therefore a common goal of nuclear, particle and astrophysics is today to understand the formation of matter from quarks and gluons.

High energy data that might shed some light on this problem are scarce.

- Deep inelastic scattering experiments on nuclei have revealed a significant variation of structure functions with the density of the nucleus. This effect was
discovered by the EMC collaboration using a high energy muon beam and subsequently investigated in detail by the NMC collaboration also at CERN. Many different explanations have been proposed in terms of shadowing, mesons in nuclei, effects of binding or modification of the nucleon size in the nuclear medium.

- Hadron production at high transverse momentum in hadron-nucleus collisions have revealed a puzzling $A^{\alpha}$ dependence with $\alpha$ varying up to 1.3. Explanations of this effect involve the successive scattering of a naked quark from quarks and gluons bound in nearby nucleons, before the formation of a hadron.

- Suppression of charmonium production has been observed in high energy heavy ion collisions. To isolate the possible signals from a quark gluon plasma, it is necessary to understand the formation and propagation of a $c\bar{c}$ pair in a dense medium.

- Proton-proton elastic scattering data at large angle measured at Brookhaven seem to be compatible with an effect of color transparency. The interpretation of these data is still controversial.

- Diffractive rho-meson production in muon scattering at very high energy shows an increase in the production rate from nuclei at high momentum transfer.

2 The ELFE project

Electrons are pointlike charges and their interaction with other elementary particles is well understood. This interaction is sufficiently weak to allow electrons to penetrate in the heart of a nucleus without significant perturbation of its structure. Electron beams probe matter with a spatial resolution that depends on their energy. The higher the energy, the better is their resolution.

During the last five years, several conferences and workshops have discussed the best experimental approach to understand the evolution from quarks to hadronic matter. Proposals using ELFE (An Electron Laboratory For Europe): a $15 \div 30$ GeV high luminosity, continuous beam electron accelerator have been discussed and collaborations have been formed at the Mainz workshop in 1992 organized by a committee composed of J. Arvieux, E. de Sanctis, T. Walcher (Chairman) and P. de Witt Huberts. This project has been presented to NuPECC at the end of 1994. These proposals form an extensive research program on exclusive reactions to probe the evolution of correlated quarks systems. Using the nucleus itself as a microscopic detector is one of the important ideas of this program. One measures the same reaction using nuclei of different sizes and thus observes the differences in the evolution from quarks and gluons to hadrons in the nuclear medium. This is possible only in the $15 \div 30$ GeV energy range. One must have sufficiently high energy to describe the reaction in terms of electron-quark scattering. However, the energy transfer should
not be too high since one is interested in the formation of hadrons inside the nuclear medium and not outside of the nucleus.

This research program lies at the border of nuclear and particle physics. Most of the predictions of QCD are only valid at very high energies where perturbation theory can be applied. In order to understand how hadrons are built, however, one is in the domain of confinement where the coupling is strong. Up to now there are only crude theoretical models of hadronic structure inspired by QCD. One hopes that in the next ten years major developments of nonperturbative theoretical methods such as lattice gauge theory will bring a wealth of results on the transition from quark to hadron. It is fundamental to guide theory by the accurate, quantitative and interpretable measurements obtained by electron scattering experiments.

The research program of ELFE addresses the questions raised by the quark structure of matter: the role of quark exchange, color transparency, flavor and spin dependence of structure functions and differences between quark distributions in the nucleon and nuclei, color neutralization in the hadronization of a quark. . . All these questions are some of the many exciting facets of the fundamental question:

“How do color forces build up hadrons from quarks and gluons? ”

ELFE will focus on the following research topics:

• **Exclusive processes.** Exclusive electroproduction processes, including polarization experiments, are needed to study the spatial structure of hadrons. Because they require coherent scattering of the quarks, exclusive observables are sensitive to the quark gluon wave function of the hadrons. Typical examples are real and virtual Compton scattering photo and electroproduction of mesons at large angle and form factors of mesons or baryons.

• **Nucleus as a detector.** The idea is to use the nucleus as a microscopic detector to determine the time evolution of the elementary quark configurations in the building up of hadrons. A typical example of this research program is color transparency in quasi-elastic reactions and in charmonium production. Another one is hadronization in the nuclear medium. For these processes, the nucleus is used as a medium of varying length.

• **Heavy Flavors.** The study of the production and the propagation of strangeness and charm provides us with an original way to understand the structure of hadronic matter. The corresponding reactions do not involve the valence quarks of the target and probe its sea quark (intrinsic strange or charm content) and gluon distributions.

• **Short Range Structure of Nuclei.** At short distances, nuclear structure cannot be reduced to nucleons or isobar configurations. To unravel such exotic configurations dedicated experiments (large x structure functions and φ production) are proposed.
3 NuPECC Recommendations

1. NuPECC has examined the case for a European CW electron accelerator in the 15-30 GeV region (ELFE) which was presented to NuPECC at the Vienna meeting in April 1994.

2. NuPECC finds the physics case compelling. The investigation of strongly interacting systems with the elementary probe of the strong interaction—the quark, produced in electron-quark scattering—is essential. Studies of hadron structure by exclusive experiments are indispensable for a better understanding of QCD in the confinement regime. New windows for the investigation of hadronic matter are opened by the use of probes with strangeness and charm.

3. NuPECC considers the potential application of highest brilliance ultrarelativistic beams in the production of coherent short wavelength radiation of high intensity to be very promising.

4. NuPECC recommends that appropriate action is taken in order to proceed towards the construction of a European facility providing electron beams of high duty cycle and brilliance in the 15-30 GeV energy range. It should serve scientists from universities and research laboratories as a central users facility.

   In order to reach this goal, the following steps need to be taken.

   a) Substantial advancement of the state of the art of superconducting RF and cryotechnology is necessary to construct such an accelerator in a cost effective way. NuPECC recognizes that significant progress has already been made. It sees important synergies with the development needed for linear colliders under consideration by particle physicists. During the next few years, an intense joint effort by the European laboratories involved is required to develop the technology further. The technical feasibility of the crucial accelerator components should be established at a testbed facility.

   b) An ELFE coordinating group should be formed by the scientific community from the field of interest, with the help of NuPECC if required. This group should coordinate the technical developments needed, and integrate the present experimental programs in electromagnetic physics in order to create an enlarged and coherent community in preparation for the long range future with ELFE. An important aspect of this the R&D work for the experimental equipment required for the physics proposed.

   c) It is important to develop further potential applications. In particular those based on coherent radiation produced by the high-brilliance beams.
A few weeks before this conference, a meeting has been organized by S. Bass in Cambridge (U.K.) to discuss how to implement these recommendations in the present European context. The possibility of using a superconducting linear accelerator injecting electrons in the HERA ring used as a stretcher has been discussed by Brinkmann. This fall a group of European accelerator physicists will start to investigate this possibility. At its next meeting in September, NuPECC is expected to propose the formation of an initiative group to organize the work between European physicists interested in this project.

4 Exclusive reactions: A new tool

Exclusive reactions are processes in which the final state is completely resolved. They are important since at high momentum transfers, they are sensitive to the quark composition themselves as expressed by quark distribution amplitudes.

To probe hadronic structure at very small distances \( \lambda \) we must transfer to the target a large momentum transfer \( Q = 1/\lambda \). The recoil kinetic energy being usually larger than the rest mass of the hadron, one is led to use a relativistic framework. Feynman was the first to show that by looking at the hadron from an infinite momentum frame, one develops an intuitive understanding of relativistic collisions. This leads to view hadrons as a collection of quasi-free objects, the partons, sharing each a fraction \( 0 < x_i < 1 \) of the infinite momentum and moving closely parallel to it. They are bound by the strong color force but their binding energy being small compared to their momentum, they behave almost freely. The parton model is for photon-hadron interactions what the impulse approximation is for nuclei. The major difference is that partons cannot be directly observed due to the existence of confinement.

Nearly all existing data on quark distributions in hadrons have been obtained by inclusive scattering of high energy particles. In such reactions, one strikes quarks with considerable momentum and energy and reconstructs quark distributions from scattering data. This is possible because of a property of factorization of the scattering amplitudes in quantum field theory. This property has allowed theory to find a firm basis for the partonic description and to go beyond the original model proposed by Feynman and Bjorken. The experimental observation amounts to an average over all the possible quark configurations in the nucleus. In addition to fundamental tests of QCD, the measurements of structure functions have lead to the discovery of the importance of gluons in the momentum and spin distributions in the proton.

We now need to go further and understand how simple quark configurations are controlled by confining mechanisms. One needs a different type of data sensitive to the time evolution of a system of correlated quarks. This is the domain of exclusive reactions where scattered particles emitted in a specific channel are observed in coincidence.

In exclusive reactions [9], one first writes the wave function of a composite state as a simple expansion of Fock states with a fixed number of quarks and gluons:
\[ |\pi\rangle = \Psi_v |q\bar{q}\rangle + \Psi_g |q\bar{q}, g\rangle + \Psi_{qg} |q\bar{q}, q\bar{q}\rangle \]  
\[ |N\rangle = \Psi_V |qqq\rangle + \Psi_g |qqq, g\rangle + \Psi_{qg} |qqq, q\bar{q}\rangle + \ldots \]

where the valence component \( \Psi_V \) turns out to be the dominant one in exclusive reactions.

Here the quarks are “current” quarks and not “constituent” ones. A constituent quark may be seen as a complex structure consisting of a current quark “dressed” of quark-antiquark pairs and gluons. Constituent quarks are important to get an intuitive picture of the quark structure of the nucleon, but they cannot be used to understand quark dynamics in the framework of a relativistic quantum field theory.

The valence wave functions \( \Psi_V \) are functions of light-cone momentum fraction \( x_i \), transverse momentum \( p_T \) and helicities. They contain important information on quark confinement dynamics. By integrating \( \Psi_V \) over transverse momenta, one gets the distribution amplitude \( \phi(x_i) \).

The analysis of leading QCD corrections to any exclusive amplitude has shown that these distribution amplitudes obey a renormalization group equation, leading to a well understood evolution in terms of perturbative QCD. At asymptotic \( Q^2 \), the distribution amplitudes simplify, e.g. for the proton:

\[ \phi(x_1, x_2, x_3, Q^2) \rightarrow x_1 x_2 x_3 \delta(1 - x_1 - x_2 - x_3) \]  

The \( Q^2 \) evolution is however sufficiently slow for the distribution amplitude to retain much information at measurable energies on confinement physics. The experimental strategy of ELFE physics is thus to sort out the hadron distribution amplitudes from various exclusive reactions to learn about the dynamics of confinement. This is possible thanks to the fact that, within perturbative QCD, one derives a factorization property of exclusive scattering amplitudes which may be schematically written as:

\[ \mathcal{M} = \phi(x_i, Q^2) \otimes T_H(x_i, y_i, Q^2) \otimes \phi^*(y_j, Q^2) \]  

where integrals over momentum fractions \( x_i \) and \( y_j \) are implicit. The hard scattering \( T_H \) is calculable perturbatively as an expansion in \( \alpha_s(Q^2) \) free of large logarithmic corrections. The functions \( \phi_i \) are the non perturbative distribution amplitudes describing the valence quark content of the proton.

One may ask the question whether existing high energy electron accelerators designed to study electroweak physics give access to these distribution amplitudes. This is not possible because of the smallness of exclusive amplitudes at large transfers. Let us illustrate this point by a back of the envelope order of magnitude estimate; take \( Z_0 \) decays as measured in great details at LEP. From the known decay rate into an electron-positron pair (around 3 per cent) and the counting rules for meson form factors, one infers that the decay rate to an exclusive light meson pair is less than...
one billionth. Accelerators designed for studying electroweak physics or QCD in inclusive reactions do not give us an access to the dynamics of confinement.

The only possibility is to use a dedicated high intensity continuous beam electron accelerator to study exclusive reactions at large transfer.

5 The Nucleus as a femto-detector

A central idea of the ELFE project is to use the nucleus as a microscopic detector to determine the time evolution of the elementary quark configurations in the building up of hadrons. Two typical examples of this research program are color transparency in quasi-elastic \((e,e'p)\) reactions and in charmonium production, and hadronization in the nuclear medium. For these processes, the nucleus is used as a medium of \textit{varying length}.

The typical time scales to build up a hadron is \(\tau_o \sim 1 \text{ fm/c} \) in its rest frame. This is the time needed by a quark to travel through distances characteristics of confined systems. Due to the Lorentz dilation factor \(\gamma = E/M\), the time scale \(\tau\), in the laboratory frame, is several \(\text{fm/c}'s\).

\textit{At this scale, the only available detector is the nucleus.}

Color transparency has been recently extensively discussed\cite{10}. This phenomenon illustrates the power of exclusive reactions to isolate simple elementary quark configurations. The experimental technique to probe these configurations is the following:

- For a hard exclusive reaction, say electron scattering from a proton, the scattering amplitude at large momentum transfer \(Q^2\) is suppressed by powers of \(Q^2\) if the proton contains more than the minimal number of constituents. This is derived from the QCD based quark counting rules, which result from the factorization of wave-function-like distribution amplitudes. Thus protons containing only valence quarks participate in the scattering. Moreover, each quark, connected to another one by a hard gluon exchange carrying momentum of order \(Q\), should be found within a distance of order \(1/Q\). Thus, at large \(Q^2\) one selects a very special quark configuration: all connected quarks are close together, forming a small size color neutral configuration sometimes referred to as a \textit{mini hadron}. This mini hadron is not a stationary state and evolves to build up a normal hadron.

- Such a color singlet system cannot emit or absorb soft gluons which carry energy or momentum smaller than \(Q\). This is because gluon radiation — like photon radiation in QED — is a coherent process and there is thus destructive interference between gluon emission amplitudes by quarks with “opposite” color. Even without knowing exactly how exchanges of soft gluons and other constituents create strong interactions, we know that these interactions must be turned off for small color singlet objects.
An exclusive hard reaction will thus probe the structure of a *mini hadron*, i.e. the short distance part of a minimal Fock state component in the hadron wave function. This is of primordial interest for the understanding of the difficult physics of confinement. First, selecting the simplest Fock state amounts to the study of the confining forces in a colorless object in the "quenched approximation" where quark-antiquark pair creation from the vacuum is forbidden. Secondly, letting the mini-state evolve during its travel through different nuclei of various sizes allows an indirect but unique way to test how the squeezed mini-state goes back to its full size and complexity, *i.e.* how quarks inside the proton rearrange themselves spatially to "reconstruct" a normal size hadron. In this respect the observation of baryonic resonance production as well as detailed spin studies are mandatory.

To the extent that the electromagnetic form factors are understood as a function of $Q^2$, $eA \rightarrow e'(A-1)p$ experiments will measure the color screening properties of QCD. The quantity to be measured is the transparency ratio $T_r$, which is defined as:

$$ T_r = \frac{\sigma_{\text{Nucleus}}}{Z\sigma_{\text{Nucleon}}} $$

At asymptotically large values of $Q^2$, dimensional estimates suggest that $T_r$ scales as a function of $A^{\frac{2}{3}}/Q^2$. The approach to the scaling behavior as well as the value of $T_r$ as a function of the scaling variable determine the evolution from the pointlike configuration to the complete hadron. This highly interesting effect can be measured in quasieleastic electron proton scattering ($e, e'p$) reaction that provides the best chance for a quantitative interpretation.

A first experiment at SLAC (NE-18) [11] has performed a preliminary exploration of Color Transparency with the ($e, e'p$) reaction for H, C, Fe and Au, in the $Q^2$ range of 1–7 GeV$^2$. In these kinematics, no effect was observed.

6 **Accelerator and detectors**

The choice of the energy range of 15 to 30 GeV for the ELFE accelerator is fixed by three constraints:

- Hard electron-quark scattering: one must have sufficiently high energy and momentum transfer to describe the reaction in terms of electron-quark scattering. The high energy corresponds to a very fast process where the struck quark is quasi-free. High momentum transfers are necessary to probe short distances.

- Nuclear sizes: The energy of the incident electron beam is determined to match the characteristic interaction time $\tau$ to the diameter of the nucleus. Starting from the rest frame time $\tau_o \sim 1$ fm/c and taking into account a typical Lorentz dilation factor $\gamma = E/M$ this means a time $\tau$ of several fm/c’s in the laboratory. If the energy transfer is too large, the building-up of hadrons occurs outside the nucleus which can then no longer be used as a microscopic detector.
Charm production requires a minimum electron beam energy of 15 GeV to have reasonable counting rates.

| Beam Energy   | 15 ÷ 30 GeV |
|--------------|-------------|
| Energy Resolution FWHM | $3 \times 10^{-4}$ @ 15 GeV |
|              | $10^{-3}$ @ 30 GeV |
| Duty Factor  | ≃ 100 % |
| Beam Current | 10 ÷ 50 µA |
| Polarized Beams | $P > 80 \%$ |

Table 1: ELFE Accelerator Parameters

Exclusive and semi-inclusive experiments are at the heart of the ELFE project. To avoid a prohibitively large number of accidental coincident events a high duty cycle is imperative. The ELFE experimental program also requires a high luminosity because of the relatively low probability of exclusive processes. Finally a good energy resolution is necessary to identify specific reaction channels. A typical experiment at 15 GeV (quasielastic scattering for instance) needs a beam energy resolution of about 5 MeV. At 30 GeV the proposed experiments require only to separate pion emission. These characteristics of the ELFE accelerator are summarized in table 1.

Due to the very low duty cycle available at SLAC and HERA (HERMES program) one can only perform with these accelerators inclusive experiments and a limited set of exclusive experiments.

ELFE will be the first high energy electron beam beyond 10 GeV with both high intensity and high duty factor.

The various components of the ELFE experimental physics program put different requirements on the detection systems that can be satisfied only by a set of complementary experimental equipment. The most relevant detector features are the acceptable luminosity, the particle multiplicity, the angular acceptance and the momentum resolution. High momentum resolution ($5 \times 10^{-4}$) and high luminosity ($10^{38}$ nucleons/cm²/s) can be achieved by magnetic focusing spectrometers. For semi-exclusive or exclusive experiments with more than two particles in the final state, the largest possible angular acceptance ($\sim 4\pi$) is highly desirable. The quality and reliability of large acceptance detectors have improved substantially in the last two decades. The design of the ELFE large acceptance detectors uses state of the art developments to achieve good resolution and the highest possible luminosity.
7 CONCLUSIONS

The ELFE research program lies at the border of nuclear and particle physics. Most of the predictions of QCD are only valid at very high energies where perturbation theory can be applied. In order to understand how hadrons are built, however, one is in the domain of confinement where the coupling is strong. It is fundamental to guide theory by the accurate, quantitative and interpretable measurements obtained by electron scattering experiments, in particular in exclusive reactions.

This research domain is essentially a virgin territory. There is only a limited amount of experimental data with poor statistics. It is not possible to make significant progress in the understanding of the evolution from quarks to hadrons with the available information.

This lack of data explains to a large extent the slow pace of theoretical progress. The situation will considerably improve due to technical breakthroughs in electron accelerating techniques. ELFE will be the first high energy machine offering the high luminosity and high duty cycle demanded by the exclusive reaction program.

A few topics of the experimental program proposed at ELFE can be covered by existing or planned facilities at the price of considerable efforts. This is the case of the proton electric form factor at SLAC. Also the proton transverse spin structure function can be studied at RHIC through dilepton pair production in polarized proton-proton collisions. These topics are but a small part of the extensive ELFE research program. The exploratory program on color transparency at Brookhaven with protons and at SLAC with electrons did strengthen the need for dedicated experiments with high energy resolution and high duty cycle electron beam. The HERMES program at HERA proposes a first detailed study of semi-inclusive reactions. ELFE experiments will increase the statistics by orders of magnitude thus allowing a much more detailed understanding of color neutralization.

The goal of the ELFE research program, starting from the QCD framework, is to explore the coherent and quark confining QCD mechanisms underlying the strong force. It is not to test QCD in its perturbative regime, but rather to use the existing knowledge of perturbative QCD to determine the reaction mechanism and access the hadron structure.

ELFE will use the tools that have been forged by twenty years of research in QCD, to elucidate the central problem of color interaction: color confinement and the quark and gluon structure of matter.

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