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Physics with a 15 ÷ 30 GeV Electron Accelerator (ELFE).

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Abstract

This paper presents a brief overview of the physics with a 15-30 GeV continuous beam electron facility proposed in Europe.

1 INTRODUCTION

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. 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 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.

Until now, the study of nuclear structure has mostly focused on the distributions of nucleons and mesons in nuclei. Experimental results have shown that even in the dense nuclear interior, nucleons keep their identity. A coherent description of nuclei at the fermi 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. In order to describe very short range processes, one must introduce more and more mesons. The limits of the description of nuclei in terms of nucleons and mesons will be studied in Europe with the accelerators of Amsterdam, Bonn and Mainz. In the United States research at CEBAF, the 4 GeV continuous beam electron accelerator built at Newport News (Virginia), will start operation in 1995. CEBAF will explore in details the structure of the nucleon and its resonances.

Although one knows the microscopic theory for the strong interactions, *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 hadrons from quarks and gluons. This is the central problem to solve if one wants to understand the formation of matter.

The advantages of electron scattering

Electron scattering is the most appropriate probe to attack this problem. 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.

Exclusive reactions: A new tool

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 reconstruct quark distributions from scattering data. The experimental observation amounts to an average over all the possible quark configurations in the nucleus. Therefore, it is impossible to get precise information on specific configurations and to follow their evolution which is controlled by the 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 inclusive scattering, the energy ν and the four momentum Q^2 of the virtual photon are the only two independent kinematic variables. In exclusive scattering, t the momentum transfer between the photon and the detected hadron, is a new variable to tune the size of the interaction volume. The production of heavy flavors and the determination of spin observables open new possibilities to disentangle various aspects of the dynamics.

The study of exclusive reactions is not possible with existing accelerators because of their technical limitations. Muons and neutrino beams have too low an intensity. Existing high energy electron accelerators have too small a duty factor.

The ELFE project

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. This project will be presented to NUPECC at the end of 1993. 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? "

PUZZLING EFFECTS OBSERVED IN HIGH ENERGY EXPERIMENTS

- 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^{α} dependence with α 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.
- Contrary to perturbative QCD predictions, helicity non conservation has been observed in several hard exclusive reactions.

2 ELFE EXPERIMENTAL PROGRAM

The central idea of the ELFE project is to use exclusive reactions and 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 *varying length.*

The typical time scales to build up a hadron is $\tau_o \sim 1$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 τ, in the laboratory frame, is several fm/c's.

At this scale, the only available detector is the nucleus.

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 virtual Compton scattering and form factors of mesons or baryons.
- *Nucleus as a detector.* A central 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 ACCELERATOR AND DETECTOR REQUIREMENTS

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 τ 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 τ 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.

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 ??.

Beam Energy	$15 \div 30 GeV$
Energy Resolution FWHM	3×10^{-4} @ 15 GeV
	10^{-3} @ 30 GeV
Duty Factor	$\simeq 100$ %
Beam Current	$10 \div 50 \mu$A
Polarized Beams	$P > 80$ %

Table 1: ELFE Accelerator Parameters

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 (5×10^{-4}) and high luminosity (10^{38} nucleons/cm^2/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.

ELFE belongs to a coherent long term strategy

Complementary experiments to study the quark structure of matter have been proposed with ultra high energy heavy ions. Thus, the experimental strategy follows two distinct paths.

- Study of the evolution from quasi free quarks or correlated quark systems to massive particles (hadrons) where they are confined. We propose in this report to build a 15-30 GeV continuous beam electron accelerator to study specific reaction channels to well identified final states. ELFE: an Electron Laboratory For Europe, dedicated to the study of the quark and gluon structure of matter.
- Study of quark deconfinement in heavy ion collisions at ultra high energies to discover the quark gluon plasma. The United States are now building the relativistic heavy ion collider (RHIC) at Brookhaven. In Europe, an exploratory program has started at CERN. An ambitious program proposes to use the future large hadron collider (LHC) at CERN.

4 COLOR TRANSPARENCY: A TYPICAL EXAMPLE

Color transparency has been extensively discussed at this workshop. 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 *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:

$$T_r = \frac{\sigma_{Nucleus}}{Z\sigma_{Nucleon}} \tag{1}$$

At asymptotically large values of Q^2, dimensional estimates suggest that T_r scales as a function of $A^{\frac{1}{3}}/Q^2$. 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 an $e,e'p$ reaction that provides the best chance for a *quantitative* interpretation.

The interplay between the perturbative and non-perturbative aspects of QCD cannot be easily explored by existing high energy machines. The SLAC electron machine is of a suitable energy, but its 10^{-4} duty factor is too low for high statistics coincidence measurements. CEBAF is capable of delivering the required beam characteristics, but its energy is too low to observe a significant effect in transparency experiments.

5 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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