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EXPERIMENTS WITH POLARIZED ELECTRON BEAMS AT HERA

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Résumé - Les anneaux de stockage des électrons et des protons "HERA" qui est en construction à DESY permettront de produire des énergies du centre de masse de plus de 300 GeV. Ce rapport traite de l'utilisation d'électrons polarisés longitudinalement pour l'étude des processus des interactions faibles et pour la recherche de nouveaux courts et de nouvelles particules.

Abstract: The electron proton storage ring HERA under construction at DESY will provide center of mass energies of more than 300 GeV. The use of longitudinally polarized electrons in the study of electroweak processes and the search for new currents and new particles will be discussed.

I. INTRODUCTION

Deep inelastic lepton nucleon scattering has played a fundamental role in exploring the smallest constituents of matter and the forces between them. The early experiments with electron beams revealed the existence of partons as pointlike and almost free scattering centers in the nucleon and showed at the same time that about half of the nucleon momentum was carried by electrically neutral objects called "gluons". From a comparison with neutrino data it became clear that the partons could be identified with the quarks of the SU(3) symmetry of hadrons. These experimental observations were the basic ingredients of Quantum Chromodynamics. Neutrino reactions provided much further insight, in particular the discovery of weak neutral currents which was one of the most important steps towards a unification of electromagnetic and weak interactions.

The electron proton collider HERA now under construction at DESY enables to extend the inelastic lepton nucleon scattering into an entirely new regime. The center of mass energy of more than 300 GeV is in fact equivalent to that of a 50 TeV lepton beam impinging on a stationary target. At HERA, electromagnetic and weak reactions can be studied simultaneously and are of comparable magnitude. Momentum transfers well above the weak boson masses are accessible and substructures in the proton can be investigated down to a scale of $10^{-17}$ cm.

One of the unique features of the HERA collider is the possibility to obtain longitudinally polarized electron or positron beams. The emission of synchrotron radiation leads to a natural transverse polarization of up to 92% with a buildup time of 20 minutes at 30 GeV. Magnet arrangements called "spin rotators" serve to rotate the spin into the beam direction in front of an interaction region and back into the transverse orientation behind it. A degree of longitudinal polarization of 60 - 80% seems feasible. With such left- or right-handed lepton beams the Standard Model of electroweak interactions can be tested in great detail. If new particles should be found at HERA like heavy leptons or quarks, leptoquarks or supersymmetric particles the polarization will be essential to determine the helicity nature of their couplings to known or new currents.

An important quantity to characterize the physics potential of a new accelerator is the number of events which can be collected in a reasonable amount of running time. The design luminosity of HERA is $6 \times 10^{31}$ cm$^{-2}$s$^{-1}$ but for a conservative estimate I shall use a value of $1 \times 10^{31}$ cm$^{-2}$s$^{-1}$ leading to an integrated lumino-
sity of 1 pb⁻¹ per day. Fig.1 shows the rate of neutral and charged current events with momentum transfers $Q^2$ larger than a given $Q_0^2$. About ten events of each type are expected per day with momentum transfers above the W mass.

In the quark-parton picture the reactions $ep \rightarrow eX$ and $ep \rightarrow \nu X$ are mediated by gauge bosons ($\gamma$, $Z^0$ or $W^\pm$) which are exchanged between the lepton and one of the quarks or antiquarks in the nucleon (Fig. 2a).

**Fig. 1**
Counting rates for charged and neutral current reactions with $Q^2$ above a given $Q_0^2$. The curves have been computed by P. Mättig (DESY) using the Glück, Reya, Hoffmann parametrization of the proton structure functions and $\Lambda_{QCD} = 100$ MeV.

**Fig. 2a** - Diagram for deep inelastic lepton nucleon scattering. The four-momenta of the incoming and outgoing lepton, the proton and the exchanged field quantum are denoted by $k$, $k'$, $p$ and $q$, respectively; $xp$ is the four-momentum of the struck quark. The variables used are $q = k-k'$, $Q^2 = -q^2$, $x = Q^2/(2p \cdot q)$, $y = (p \cdot q)/(k \cdot p)$. For protons at rest: $p \cdot q = M\nu = M(E-E')$, $x = Q^2/2M\nu$, $y = \nu/E$. 
The scattered lepton appears on one side of the proton beam, the struck quark transforms into a narrow bundle of hadrons called "current jet" on the opposite side. The remainders of the proton produce a jet of hadrons moving along the proton beam direction. Monte Carlo simulations of such events (Fig. 2b) show that the outgoing lepton and the current jet are very well separated from each other and from the proton jet. HERA is thus ideally suited to study lepton-quark collisions without "background" from spectator quarks. The events have a very distinct topology and can be easily recognized. It appears rather unlikely to confuse them with proton reactions on rest gas molecules in the vacuum chamber or other background.

In order to compute the proton structure functions, the kinematical quantities $Q^2$ and $x$, i.e. the squared four momentum transfer and the fractional momentum of the struck quark, have to be determined. Since the incident electron energy is well known it is sufficient to measure the energy and angle of the current jet. A hadron calorimeter with good energy and angular resolution will be an essential feature of a HERA detector.

$$e + q \rightarrow \nu + q + \text{gluon}$$

\[Q^2 = 25000 \text{ GeV}^2\]

\[x = 0.5\]

Fig. 2b - Monte Carlo simulation of an event electron + proton + neutrino + quark + gluon + X. The outgoing quark and gluon fragment into well separated hadron jets. The black dots indicate the endpoints of the momentum vectors of the hadrons. For momentum transfers $Q^2 > 10^3$ GeV$^2$ the lepton is scattered by more than 90°. (From D.H.Perkins, Ref.1).
II. - TESTS OF THE STANDARD MODEL AND SEARCH FOR NEW WEAK BOSONS

All weak processes observed so far and in particular the discovery of the $W^\pm$ and $Z^0$ bosons at the CERN pp collider are in excellent agreement with the standard model of electroweak interactions.

With HERA it will be possible to test this theory in the region of very large spacelike momentum transfers where electromagnetic and weak processes should be of equal strength. The standard model predicts quite characteristic features for neutral and charged current interactions. The cross section of the reaction $e p \rightarrow e X$, normalized to the one-photon exchange cross section, is shown in Fig. 3.

For $Q^2$ above $10^4$ GeV$^2$, the photon-$Z^0$ interference term is very large and leads to remarkable differences between left-handed and right-handed electrons and also between electrons and positrons.

![Fig. 3 - Interference between photon and $Z^0$ exchange in $e p \rightarrow e X$ with longitudinally polarized electrons or positrons. Plotted is the ratio of the standard model cross section to the one-photon exchange cross section at $x = 0.25$. (From Ref. 2).]

A question of crucial importance is of course whether additional $Z^0$ bosons exist. Polarized lepton beams allow a more sensitive search than cross section measurements. The polarization asymmetry between left-handed electrons and right-handed positrons is shown in Fig. 4. With a total integrated luminosity of 400 pb$^{-1}$, $Z_2$ masses up to 450 GeV seem accessible.
The charged current reaction $e^- + \nu X$ is mediated by $W^\pm$ exchange with purely left-handed couplings. Additional left-handed $W$ bosons can be detected at HERA even if their mass should be beyond the center-of-mass energy of 300 GeV. The reason is that the interference with the standard $W$ exchange leads to a substantial increase in counting rate at large values of $Q^2$ (see Fig. 5). $W_2$ masses up to 500 GeV can be determined. The situation is quite different if the second $W$ couples only to right-handed electrons. In that case there is no interference and the rate for $e_R^+ + \nu X$ may be quite low if the mass of the $W_R$ is high. A lower limit of 400 GeV for the mass of a $W$ boson with right-handed couplings can be derived from the decay of polarized muons \cite{4}. While it will be difficult to improve such a...
limit at HERA one has to keep in mind that the experiments at low $Q^2$ are only sensitive to right-handed currents if the neutral partner $\nu_R$ of the right-handed charged lepton is massless or very light, $m(\nu_R) < 10$ MeV. Since there is no compelling theoretical reason why right-handed neutrinos should be light, measurements at large $Q^2$ are unavoidable to either establish or rule out right-handed currents.

Fig. 5 - The cross section for the charged current reaction $e + p + \nu + X$ in a model with two left-handed W bosons, normalized to the standard model cross section. The coupling constants of the $W_1$ and $W_2$ are assumed to be the same and are adjusted such that at $Q^2 = 0$ the Fermi coupling is obtained. The counting rate at $Q^2 \geq 3 \times 10^4$ GeV$^2$ is about 100 per year at a luminosity of $1 \times 10^{31}$ cm$^{-2}$s$^{-1}$, so $W_2$ masses well above the HERA center-of-mass energy are accessible.

To get an idea on the sensitivity which might be achieved at HERA we consider the ratio $R = \sigma_R/\sigma_L$ of the right- and left-handed cross sections. Assuming that the $W_R$ couples to the normal quarks and leptons with the same strength as the standard $W_L$, this ratio is given by

$$R = \left( \frac{Q^2 + M_L^2}{Q^2 + M_R^2} \right)^2.$$
At $Q^2 = 5000 \text{ GeV}^2$ a ratio $R = 0.05$ corresponds to a $W_R$ mass of 214 GeV. For a degree of polarization of $P = 0.80 \pm 0.01$ and an integrated luminosity of 300 pb$^{-1}$, shared equally between left-handed and right-handed electron beams, one obtains a statistical significance for the cross section ratio of

$$R/\sigma(R) = 5.8.$$ 

The statistical significance depends both on the degree of polarization $P$ and on the uncertainty $\sigma(P)$. For $P = 0.60 \pm 0.02$, the statistical significance obtained with the same total luminosity is only 3.0.

III. - SUBSTRUCTURE IN QUARKS AND LEPTONS

One of the basic tasks of the HERA experiments will be to measure the proton structure functions at large $Q^2$. Systematic tests of QCD, the nature of scaling violations, an accurate measurement of $\alpha_s(Q^2)$ and a determination of the quark densities are problems of great interest. I do not want to discuss these questions but rather concentrate on the implications of a substructure. If quarks or leptons are composite a new strong force must bind the constituents. The associated field quanta are probably very massive because fermions are pointlike down to $10^{-16}$ cm. One cannot expect to observe them directly but a residual interaction, analogous to the four-fermion interaction in $B$-decay, may be detected due to its interference with the standard $\gamma$, $Z^0$ and $W^\pm$ exchanges. The new interaction can be characterized by a compositeness scale $\Lambda_H$ which is presumably above 1 TeV. Rückl has computed the change in the proton structure function $F_2(x,Q^2)$ as a function of the parameter $\Lambda_H$ (Fig. 6).

**Fig. 6**

The proton structure function $F_2(x,Q^2)$ at $x = 0.5$ for various values of the scale parameter $\Lambda_H$. The dashed and dotted curves are the standard model prediction and the one-photon exchange result, respectively.
It appears that at \( Q^2 = 3 \times 10^4 \text{ GeV}^2 \) values of \( \Lambda_H \) as high as 2-3 TeV may be detected. One has to keep in mind, however, that the quark distributions at such large \( Q^2 \) are unknown and that the standard model calculation of \( F_2(x,Q^2) \) depends on large extrapolations of present data. Polarization asymmetries are independent of such extrapolations. As an example I show in Fig. 7a the asymmetry

\[
A^- = \frac{\sigma(e_L^-) - \sigma(e_R^-)}{\sigma(e_L^-) + \sigma(e_R^-)}.
\]

Depending on the helicity nature of the lepton and quark couplings at the four-fermion vertex, the residual interaction may be visible for \( \Lambda_H \) values up to 5 TeV.

Another asymmetry which does not depend on the technically difficult longitudinal beam polarization is that between electrons and positrons (Fig. 7b). Here the sensitivity is only large if the leptons and quarks couple with opposite helicities (left-right or right-left) at the four-fermion vertex.

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**Fig. 7a** - The polarization asymmetry \( A^- = (\sigma(e_L^-) - \sigma(e_R^-)) / (\sigma(e_L^-) + \sigma(e_R^-)) \) in the standard model (dotted curve) and for various values of the substructure scale \( \Lambda_H \). The label "LL" (RR) denotes left-handed (right-handed) couplings for both the leptons and the quarks in the residual four-fermion interaction.

**Fig. 7b** - The charge asymmetry \( B_0 = (\sigma(e^-) - \sigma(e^+)) / (\sigma(e^-) + \sigma(e^+)) \) in the standard model (dotted curve) and for various values of \( \Lambda_H \).
IV - SEARCH FOR NEW PARTICLES

Electron proton collisions are ideally suited to produce new leptons which couple to the electron as well as new quarks which couple to the u and d quarks in the proton. A neutral heavy lepton $L^0$ and a heavy quark $Q$ could be produced in the reaction $e + q \rightarrow L^0 + Q$. Provided new charged currents exist which do not suppress this process through small mixing angles the rates are fairly high even for large masses of the lepton and quark (e.g. 1 event per day for $M_L = M_Q = 50 \text{ GeV}$ and a mass of the exchanged W boson of 200 GeV). The decay of the heavy lepton leads to pronounced event signatures: leptons and hadronic jets will emerge from the lepton vertex instead of the single outgoing neutrino in normal charged currents events. If such heavy leptons should be detected, measurements with longitudinally polarized electrons would be extremely valuable. Suppose the $L^0$ was found to couple to right-handed electrons only then it would be natural to assume that right-handed electrons belong into weak isospin doublets rather than into singlets as in the standard model.

Another class of particles which couple directly to either the electron or the normal quarks in the proton are their supersymmetric partners. The associated production of scalar leptons and quarks

$$e + q \rightarrow \tilde{e} + \tilde{q} \quad \text{or} \quad e + q \rightarrow \tilde{\nu} + \tilde{q}$$

proceeds through the exchange of a spin 1/2 field quantum ($\tilde{\gamma}, \tilde{Z}$ or $\tilde{W}$). The scalar electron decays into an electron and a photino, the scalar quark into a quark and a gluino or photino.

Since both $\tilde{\gamma}$ and $\tilde{q}$ are invisible the observed final state in the reaction $e + q \rightarrow \tilde{e} + \tilde{q}$ is the same as in normal neutral current events: a single electron track and a jet of hadrons. Due to the momentum and energy carried away by the photino and gluino these supersymmetric events will have a large imbalance in transverse momentum and the electron and the hadron jet will not appear back-to-back when viewed along the beam direction. By suitable cuts in coplanarity and transverse momentum these exotic events can be very well separated from conventional neutral current interactions.

The reaction $e + q \rightarrow \tilde{\nu} + \tilde{q}$ is much more difficult to identify experimentally since the nuino will in general decay into invisible particles. The final state therefore contains just a single jet of hadrons and cannot be distinguished from the much more numerous charged-current events $e + q \rightarrow \nu + q'$ at lower $Q^2$. There is, however, the possibility of more complicated decay modes of the nuino leading to multilepton or mixed lepton and hadron final states. In that case the events $e + q \rightarrow \nu + q'$ will be unmistakable.

The rate for associated production of scalar leptons and quarks has been computed by Jones and Llewellyn-Smith and by Altarelli, Mele and Rückl. Fig.8 shows the cross section at $\sqrt{s} = 314 \text{ GeV}$ as a function of the $\tilde{e}$ and $\tilde{q}$ masses. Almost 10 events per day are expected for $m_{\tilde{e}} = m_{\tilde{q}} = 40 \text{ GeV}$. The cross sections for the electroproduction of supersymmetric particles depend strongly on the lepton charge and polarization (see Ref. 6). For the charged current process $e + q \rightarrow \tilde{\nu} + \tilde{q}$ the predicted rate with left-handed electrons is significantly higher than that with right-handed positrons; for neutral current SUSY events, on the other hand, positrons give a higher yield than electrons. Measurements with polarized beams and with both electrons and positrons are highly desirable to check these predictions.
Fig. 8
The cross section for associated production of scalar electrons and quarks at $\sqrt{s} = 314$ GeV as a function of the $\bar{e}$ and $\bar{q}$ masses.
(From R.J.Cashmore, Ref.3).

V - CONCLUSION
The electron proton collider HERA opens a rich field of physics which is complementary to the physics potential of $e^+e^-$ and $p\bar{p}$ (pp) colliders. A large fraction of the physics programme can be covered with unpolarized beams like the measurement of the proton structure functions, QCD tests and search for new particles. The longitudinal electron polarization is valuable in the investigation of substructure effects; it is indispensable for detailed studies of the standard model, in the search for right handed charged currents and for determining the helicity structure of the couplings of new particles.

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