SLAC-PUB--3434
DE85 002718

RECENT PROGRESS IN ELECTRON SCATTERING AT SLAC*

Raymond G. ARNOLD
The American University, Washington D.C., 20016
and
Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94305

1. INTRODUCTION

Since the last meeting in this conference series in Paris in 1981, there has been major progress in electron scattering at SLAC on several fronts. A new experiment on *ep* elastic scattering at large momentum transfer, Experiment E136, has recently completed data taking. A new measurement of deep inelastic electron scattering from nuclear targets, Experiment E139, has been completed and preliminary results are available. A new program of experiments has begun, called Nuclear Physics at SLAC (NPAS), that will use a new injector on the SLAC linac to provide high intensity beams in the energy range from 0.5 to 6 GeV.

2. *ep* ELASTIC SCATTERING AT LARGE MOMENTUM TRANSFER

Elastic electron scattering from the proton is one of the basic reactions for learning about the structure of the proton, and therefore eventually about all hadronic matter. Prior to Experiment E136[1], *ep* elastic measurements from many laboratories over the years extended from Q^2 near zero up to a maximum $Q^2 = 33.4\ (GeV/c)^2$. The theoretical motivation has evolved with time from the first discovery that the proton was not a point particle to the eventual comparison of the electromagnetic form factor data with various models featuring a nucleon core with a meson cloud, and including the meson content of the virtual photon. After the discovery of the quark substructure of nucleons in deep inelastic scattering, the proton was imagined to be made of three pointlike valence quarks surrounded by a cloud of quark-antiquark pairs. The fractionally charged quarks were found to carry only about half of the momentum of the nucleon, but they carry all the electromagnetic charge and current, and electron scattering probes the distribution of quarks in the target. The cross section for elastic electron scattering at momentum transfer Q^2 is proportional to the probability for transforming a distribution of quark momenta at P_i in the initial state to $P_i + Q$ leaving the nucleon bound in the final state. In the early stages of the quark model a

* Work supported in part by the Department of Energy, contract DE-AC03-76SF00515 (SLAC) and National Science Foundation grant PHY83-40337 (American U.).

Talk presented at the 10th International Conference on Particles and Nuclei in Collision, Heidelberg, West Germany, July 30 – August 3, 1984.

series of scaling laws[2] for exclusive scattering processes were developed based on dimensional counting and the scale invariance of the quark-quark interaction at short distance. At large Q^2 the contribution to ep elastic from scattering on the cloud of quark-antiquark pairs is predicted to fall away faster than the contribution from scattering on the valence quarks, and the proton form factor is predicted to decrease with increasing Q^2 like $G_{M_p} \sim 1/Q^4$. The previous data, shown in Figure 1, are consistent with a nearly constant value for $Q^4 G_{M_p}$ for Q^2 greater than 10 $(GeV/c)^2$, although the precision of the data above 10 $(GeV/c)^2$ is not good enough to rule out a substantial deviation from $1/Q^4$ behavior.

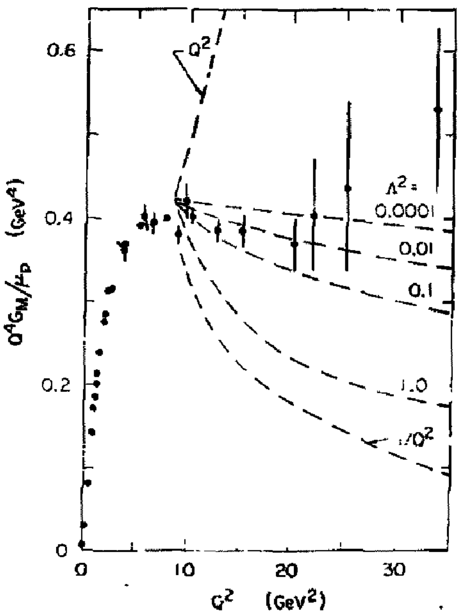


Fig. 1. Previous world data for the proton magnetic form factor G_{M_p} multiplied by Q^4 and plotted versus Q^2. The curves are perturbative QCD predictions from Ref. 4.

In recent years the theory of hadronic matter in terms of colored quarks and gluons has progressed to the point where explicit calculations of the meson and nucleon form factors in perturbative QCD are now possible[3]. Elastic ep scattering at large Q^2 can be viewed as electron-quark scattering accompanied by two hard quark-quark scatterings. The proton form factor is predicted[4] to be

$$G_{M_p} = \frac{\alpha_s^2(Q^2)}{Q^4}\phi(Q^2)$$

The $1/Q^4$ dependence comes from the propagators of the two gluons connecting the three valence quarks together, and the two powers of the strong coupling constant $\alpha_s(Q^2)$ come from the quark-gluon vertices. The factor $\phi(Q^2)$ contains the dependence on the initial and final state proton wave functions.

A measurement of ep elastic scattering with good precision over a range of large momentum transfer could be viewed, when compared with the perturbative QCD calculations, as first checking to see that $Q^4 G_{M_p}$ is nearly constant above some Q^2. That would support the assumption that only the minimal hard scattering on the valence quarks survives at large Q^2. There may be some slow, logarithmic in Q^2, deviation from $1/Q^4$ shape that causes G_{M_p} to fall faster than $1/Q^4$ due to the change in the strong coupling constant with Q^2. The amount of this deviation from perfect $1/Q^4$ behavior would depend on the size of the QCD scale parameter Λ_{QCD}, with a larger value of Λ_{QCD} giving a larger deviation. If $Q^4 G_{M_p}$ were found to rise at large Q^2, as hinted by the previous data, that would be in stark contradiction to the pertabative QCD predictions. Shown in Figure 1 are a series of curves from the perterbative QCD calculations by Brodsky and Lepage[4] for several values of Λ_{QCD}.

Recently Isgur and Llewellyn-Smith[5] have criticized the interpretation of high Q^2 ep elastic data in terms of the hard scattering process. They suggest that the proton form factor will get large contributions from soft processes out to very large Q^2. Whatever the outcome of this theoretical debate, measurement of the proton form factor at large momentum transfer will provide constraints on the range of ideas about the internal proton structure.

The primary motivation for Experiment E136 was to measure ep elastic scattering with substantially better precision than previous experiments over a large range in Q^2 to measure the slope of $Q^4 G_{M_p}$ above $Q^2 = 10\ (GeV/c)^2$. The data extend from $Q^2 = 5\ (GeV/c)^2$, where the overall error in the cross section is approximately $\pm 3\%$, out to $Q^2 = 31.5\ (GeV/c)^2$ where the statistical error dominates and is $\pm 20\%$. Data taking was completed in May 1984, and analysis is in progress.

3. DEEP INELASTIC SCATTERING FROM NUCLEI

Following the now famous discovery[6] by the EMC collaboration, subsequently verified[7] in archival SLAC data, of a difference between deep inelastic scattering on iron and deuterium, it became clear that more measurements of this effect were needed, and that the facilities at SLAC were ideal for this purpose. The 8 GeV/c spectrometer with its detectors and electronics were set up and operating for E136. All that was needed was a different target. Therefore the E136 collaboration elected to interrupt that experiment and quickly proposed and ran SLAC Experiment E139[8], a measurement of the A dependence of deep inelastic scattering (DIS). The preliminary results are published[9] and will only be briefly reviewed here.

The aim of this short experiment was to measure the A dependence of the cross section ratio σ_A/σ_d for DIS over a range of kinematics $0.1 \leq x \leq 0.9$ and $2 \leq Q^2 \leq 15$ $(GeV/c)^2$ readily accessible using the SLAC beam energy $E_i \leq 24.5\ GeV$ and the 8 GeV/c spectrometer. A primary goal was to look for the A dependence versus x at $Q^2 = 5$ $(GeV/c)^2$, which is safely in the deep inelastic scaling region. In addition we wanted to measure at $x = 0.6$ where the nuclear effect is large over a range in Q^2 to look for any possible deviation from scaling. Finally measurements were made at several values of fixed x and Q^2 but at various scattering angles to look for a possible variation with A in the ratio of longitudinal to transverse cross sections $R = \sigma_L/\sigma_T$.

The targets chosen were readily available materials of natural isotopic abundance spanning the A range from ^{4}He to ^{197}Au. Since the size of the effect was expected to be only a few percent in the ratio σ_A/σ_d, while the individual cross sections vary over several orders of magnitude, special efforts were made to keep the systematic errors in the ratio small. The overall systematic uncertainty for most kinematic points is estimated to be in the range 1% to 2% in the ratio σ_A/σ_d.

An overview of the data, obtained in approximately 80 hours of beam time, is displayed in Figure 2. The results showed no significant variation with Q^2 in the range $Q^2 = 2$ to 15 $(GeV/c)^2$, as indicated in part (a) of Figure 2, which supports the idea that the scattering takes place incoherently on individual pointlike quarks. The ratio σ_A/σ_d is not constant for any nucleus. It is less than one for $x > 0.3$, and the deviation from unity increases with nuclear size. In contrast to the EMC data[6], our data for σ_A/σ_d does not extend much above one for $x < 0.3$.

The observed difference in cross section per nucleon for nuclear targets indicates that the quark momentum distributions are distorted for nucleons embedded in nuclei. The shift in σ_A/σ_d to values below one for $x > 0.3$, where the contribution from scattering on ocean quarks is negligible, indicates a shift of momentum away from the valence quarks in that x region in nuclei. The magnitude of this shift increases smoothly with increased nuclear size, roughly proportional to the log of A, as shown in Figure 3.

Precisely where the valence quark momentum is shifted remains a subject of intense theoretical investigation and debate[12]. The suggestions are that it goes to the glue, to excess ocean quark pairs, to valence quarks at low x and to valence quarks in the kinematically forbidden region for free nucleons at $x > 1$. It is likely that all these mechanisms play a

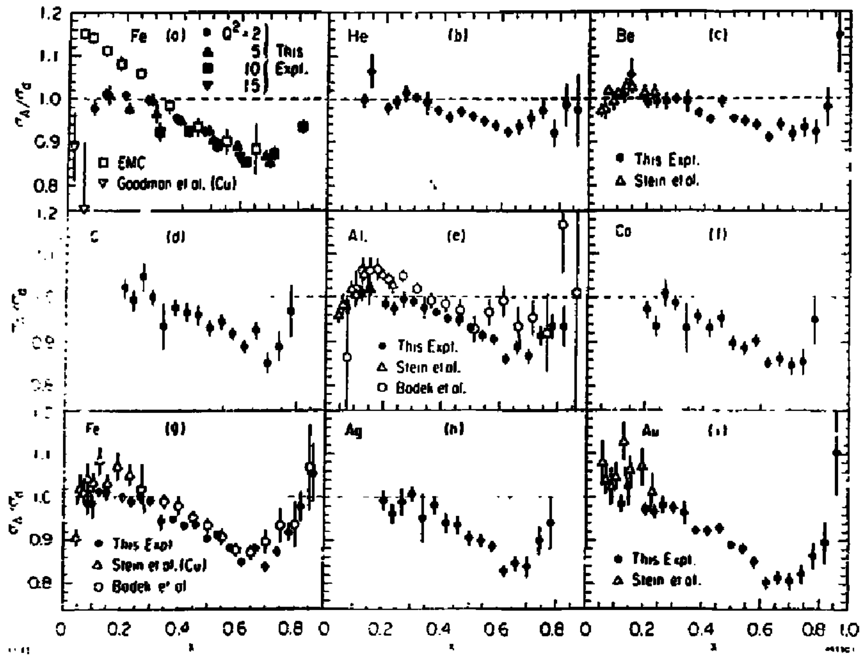


Fig. 2. (a) E139 results for σ_{Fe}/σ_d as a function of x for various values of Q^2 as well as higher energy muon data from Refs. 6 and 11. (b)-(i) σ_A/σ_d averaged over Q^2 as a function of x for various nuclei, as well as electron data from Refs. 7 and 10. The error bars are statistical only.

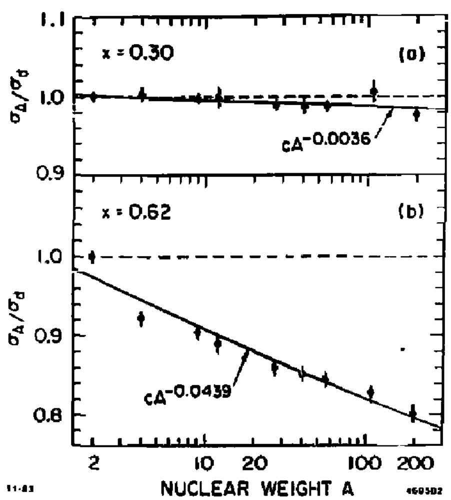


Fig. 3. E139 results for Q^2-averaged ratios σ_A/σ_d versus A at fixed x. (a) $x = 0.3$, (b) $x = 0.62$. The solid line is a fit of the form $\sigma_A/\sigma_d = cA^{\alpha}$. The errors shown are statistical only.

role to some degree. Untangling this puzzle will take time, and progress would be aided by additional data. In particular it is essential to understand the source of the disagreement between the electron experiments and the EMC experiment for $x < 0.3$. One suggestion for the difference is that nonscaling is observed, because the EMC data is predominantly at Q^2 above 10 $(GeV/c)^2$ while the electron data at $x < 0.3$ are only in the range $Q^2 = 1$ to 5 $(GeV/c)^2$. Another suggestion is that $R = \sigma_L/\sigma_T$ varies with A. Figure 4 shows the results for R versus A from the very limited data sample from E139. Since it is conceivable that R might vary with x as well as A, consider only the points at $x = 0.5$ in Figure 4. They show a slight trend to increase with A, but the data are also consistent within errors with a constant value independent of A and consistent with the average value from previous experiments on deuterium.

Another way to examine the data on R, which avoids some of the systematic uncertainties in an absolute measurement, is to look at the ratio σ_A/σ_d versus the virtual photon polarization paramater ϵ, as in Figure 5. If R is independent of A the ratio σ_A/σ_d at a given x and Q^2 would be constant versus ϵ. The sloped lines in Figure 5 were obtained by fitting straight lines to the six data points at $Q^2 = 5$ $(GeV/c)^2$ and $x = 0.3$, 0.5, and 0.7, using the same slope versus ϵ at all x. The data for the other Q^2 values not used in the fit are then plotted for comparison. While the better agreement of all the data with the sloped lines is suggestive ($\chi^2 = 16$ for 14 degrees of freedom for the sloped lines versus $\chi^2 = 35$ for zero slope), the limited range and precision of this data cannot be taken as proof of variation of R with nuclear size. It is, however, amusing to notice the effect such a variation has upon the extraction of the deep inelastic structure functions F_2 at $\epsilon = 1$ from the E139 data, as shown in Figure 6. Note that the EMC data is measured close to $\epsilon = 1$ and thus extraction of F_2 from their cross sections is not very sensitive to uncertainty in R. The improvement in agreement with the EMC data at low x is significant, although the systematic uncertainties on the E139 data are large due to the extrapolation to $\epsilon = 1$.

The main conclusion to be drawn from these observations is that there is a substantial sensitivity at low x to a possible variation of R with A. It remains a mystery why R should vary with nuclear size. More measurements of σ_A/σ_d in the region below $x = 0.3$ are needed to sort out any possible Q^2 dependence. Also more extensive and accurate measurements of R versus A are needed to see if the present hint of A dependence is real.

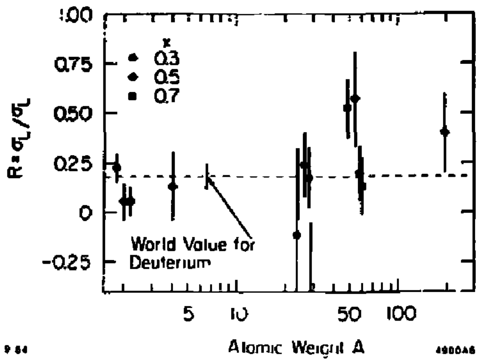


Fig. 4. E139 results for $R = \sigma_L/\sigma_T$ at $Q^2 = 5$ $(GeV/c)^2$ and various x values versus nuclear weight A. The errors are statistical only. The average SLAC value and error for deuterium are also shown.

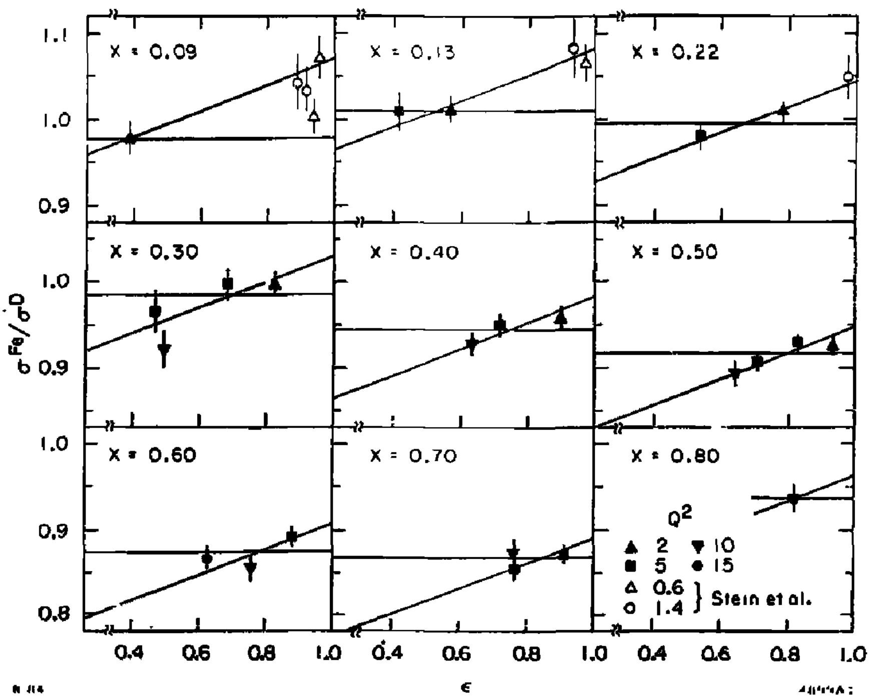
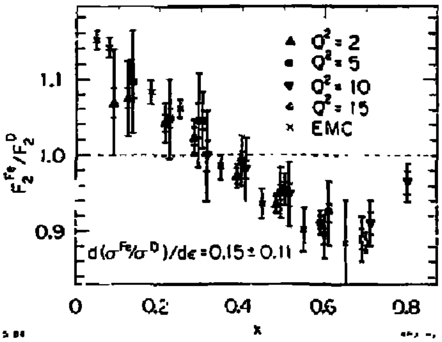


Fig. 5. E139 results for σ_{Fe}/σ_d at various x and Q^2 values versus the virtual photon polarization parameter ϵ. The error bars are statistical only. Also shown are data from a Cu target from Ref. 10.

Fig. 6. E139 results for the ratio of deep inelastic structure functions per nucleon F_2^{Fe}/F_2^d extracted at $\epsilon = 1$ from measurements of the section ratios σ_A/σ_d at various ϵ using the slope $d(\sigma_{Fe}/\sigma^d)/d\epsilon = 0.15 \pm 0.11$ shown in Figure 5. The inner error bar is the statistical error, while the outer bar indicates the additional systematic uncertainty from the extrapolation to $\epsilon = 1$. Also shown are the EMC data from Ref. 6.



4. A NEW PROGRAM OF NUCLEAR PHYSICS AT SLAC

A new program of experiments, called Nuclear Physics at SLAC (NPAS) has recently been approved and funded and is now underway. This program is based upon a new high intensity electron beam to be produced by a new injector, called the Nuclear Physics Injector (NPI), under construction at a point 20% from the downstream end of the SLAC linac[13]. The NPI will produce electron beams in the energy range 0.5 to 6 GeV with intensity larger by factors of 10 to 50 than presently available from the full SLAC linac in that energy range.

The NPI is expected to deliver usable electron beams into End Station A in late 1984. The NPAS program is a national facility open for competitive proposals from all qualified experimenters. The SLAC Associate Director for the Research Division, R. Taylor, acts as program Director, and R. Arnold, American University, serves as program Coordinator. Physics program decisions are made by the Associate Director, upon the advice of the Nuclear Program Advisory Committee (NPAC), chaired by E. Vogt, TRIUMF.

At its first meeting in May 1984 the NPAC recommended approval of four experiments. Experiment NE3, proposed by a collaboration from the University of Virginia and Basel Switzerland, will measure inclusive electron scattering in the 8 GeV/c spectrometer from a number of nuclei in the kinematic region $x \geq 1$. Experiment NE4, proposed by a collaboration from The American University, Universitat Bonn, University of Massachusetts, and SLAC, will measure elastic and inelastic electron scattering from deuterium at large momentum transfer and scattering angles around 180 degrees. A special 180 degree double arm spectrometer will be constructed in End Station A. The two experiments NE1 and NE5, proposed by collaborations from Argonne, University of Virginia, and Florida State University, will measure inelastic electron scattering from nuclei at Q^2 below 1 $(GeV/c)^2$ in the region of excitation of the delta nucleon resonance using the 1.6 GeV/c and the 8 GeV/c spectrometers.

For the future[14] at SLAC, there now exist in various stages of discussion and planning several ideas for new experiments. A proposal is in preparation by an American Univ.-Univ. of Rochester collaboration to measure $R = \sigma_L/\sigma_T$ in the deep inelastic region on the proton, deuteron, and selected heavier nuclei. Work has recently begun by an American Univ.-MIT collaboration on plans to secure approval for a tritium target at SLAC for measurements of the elastic ^3H form factors and a comparison of deep inelastic scattering from ^3H and ^3He. Space has been reserved for a polarized electron source in the NPI, and someday experiments to measure neutron and deuteron electromagnetic form factors using the spin transfer method[15] and measurements of electro-weak interference may be possible.

REFERENCES

1. The E136 collaboration includes The American Univ.:, R. Arnold, P. Bosted, C. Chang (on leave from Univ. of Maryland), J. Gomez, A. Katramatou, J. Lambert (on leave from Georgetown Univ., Wash. D.C.), R. Lombard (on leave from CEN Saclay), J. Martoff (present address Stanford Univ., Stanford CA.), A Rahbar, S. Rock, Z. Szalata; and SLAC: D. Sherden.
2. S. Brodsky and G. Farrar, Phys. Rev. **D11**,1309(1975); S. Brodsky and B. Chertok, Phys. Rev. **D14**, 3003(1976).
3. An excellent review of perterbative QCD with extensive references is given in S.J. Brodsky, T. Huang, G. P. Lepage, SLAC PUB 2868 (1982), published in the Proceedings of the Ninth Summer Inst. on Particle Physics, SLAC (1981),The Banff Summer Inst. in Particles and Fields, Banff Alberta Canada (1981), and the KfK Summer School on Quarks and Nuclear Forces, Bad Liebenzell, Germany (1981).
4. S. Brodsky, G. Lepage, Phys. Rev. **D22**, 2157(1980).
5. N. Isgur and C. Llewellyn-Smith, Phys. Rev. Lett. **52**, 1080(1984).
6. J. Aubert, *et al*, Phys. Rev. Lett. **123B**, 275(1983).
7. A. Bodek, *et al*, Phys. Rev. Lett. **50**, 1431;**51**, 534(1983).
8. The E139 collaboration included those in Ref 1 and Univ. of Rochester: A. Bodek, N. Giokaris (present address Fermilab, Batavia Ill.); and Univ. Bonn: B. Mecking.
9. R. Arnold, *et al*, SLAC PUB 3257 (1984); Phys. Rev. Lett. **52**, 727(1984).
10. S. Stein, *et al*, Phys. Rev. **D12**, 1884(1975).
11. M. Goodman, *et al*, Phys. Rev. Lett. **47**, 293(1981).
12. The publications to date on the EMC effect are too numerous to list here. See the review talks at this conference by S. Winpenny and C.H. Llewellyn-Smith for references to the experimental and theoretical literature.
13. Details of the electron beam, experimental facilities, and program operation are available in the NPAS Users Guide, SLAC Report 269 (1984).
14. A recent review of possible future experiments using high energy electrons is given in R. Arnold, Proceedings of the 10^{th} International Conf. on Few-Body Problems in Physics, Karlshrue, West Germany, Aug. 22-27 (1983), Ed. B. Zeitnitz.
15. R. Arnold, C. Carlson, and F. Gross, Phys. Rev. **C23**,363(1981).