SLAC-PUB-3216
September 1983
(T/E)

FUTURE EXPERIMENTS ON QCD EFFECTS IN FEW NUCLEON SYSTEMS WITH HIGH ENERGY ELECTRONS

R. G. ARNOLD*
The American University, Washington, D.C. 20016 and
Stanford Linear Accelerator Center
Stanford University, Stanford, California 94305

1. INTRODUCTION

A central question in the study of the few nucleon systems today is how to understand nuclear structure in terms of the quark degrees of freedom. It is now clear that nucleons are composite, and that QCD, the gauge theory of colored quarks and gluons, is probably the correct theory of hadronic matter. The question is: At what points in our description of nuclear structure do we have to abandon the conventional meson-nucleon theory in favor of quarks? In this talk I review some of the evidence for quarks in nuclei from previous high energy ($E > 1$ GeV) electron scattering experiments.[1-6] There is a great need for more electron data on nuclear targets. In response to that need there are now plans for more experiments in the near future.

2. WHERE TO LOOK FOR QUARKS?

Examination of the present high energy electron scattering data on the nucleons and the $A \leq 4$ nuclei yields the following observations:

A. There appears to be a gradual transition from the conventional nuclear physics regime to the quark regime in the high energy electron data. As the energy and momentum transfer to the hadronic system increases from the MeV range to the GeV range, there is a gradual change from coherent scattering off collections of quarks (nucleons, mesons, isobars) to scattering from individual point-like quarks (scaling region). This transition takes place in the momentum transfer Q^2 range up to approximately 4 (GeV/c)^2, and can be seen in both the elastic and inelastic data. In Fig. 1 the elastic form factors of the nucleons and the nuclei $A \leq 4$ are observed to gradually approach the power law fall-off with increasing Q^2 predicted by the quark counting rules.[7] The power law behavior follows directly from the dominance at large Q^2 of the minimal n quark component of the hadronic wave function, and the scale invariance of the quark-quark interaction at short distances (quarks are point-like), up to logarithmic corrections. Figure 2 shows a schematic[8] of the proton structure

---

*This work was supported by the Department of Energy under contract DE-AC03-76SF00515, and by the National Science Foundation under grants PHY-8108484 and PHY83-40337.

Invited talk to the 10th International Conference on Few Body Problems in Physics
Karlsruhe, West Germany, August 22-27, 1983.

functions derived from *ep* data[9] covering the elastic peak, the nucleon resonances, and the deep inelastic region. The peaks from coherent scattering sink into the continuum of incoherent scattering from individual point-like quarks as the Q^2 is raised to 3 or 4 $(\mathrm{GeV/c})^2$. For inelastic scattering from nuclei the picture is similar except the nucleon resonant structures are smeared out due to Fermi motion and interactions in the nuclear medium.

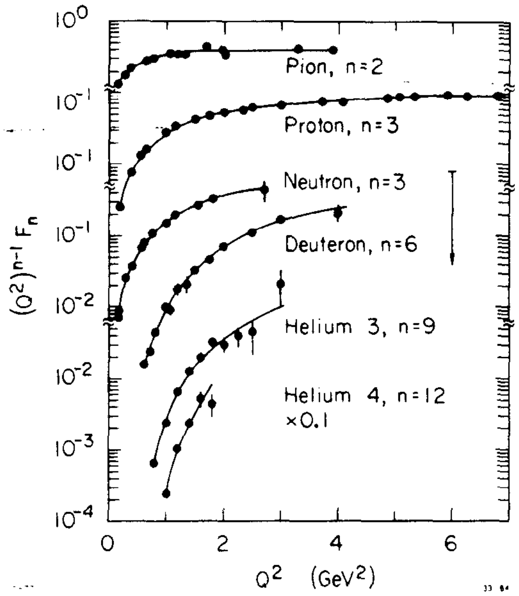

FIGURE 1. Elastic form factors $F = \sqrt{A(Q^2)}$ of the hadrons and $A \leq 4$ nuclei multiplied by the power of Q^2 determined for each n quark system by the dimensional scaling quark model (ref. 7).

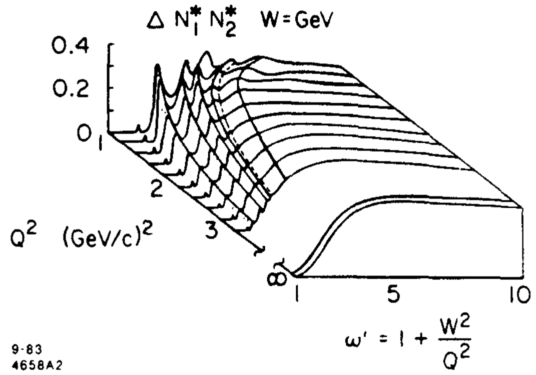

FIGURE 2. Schematic representation of the electron proton structure functions νW_2 at high energies. The figure is from ref 8, based upon data in ref. 9.

B. There is a systematic pattern of deviations of the present high energy electromagnetic structure function data from the predictions of the conventional meson-nucleon models. These models generally give too small values for the cross sections at large Q^2. In the deuteron $A(Q^2)$, for example, the conventional nonrelativistic models[10] fall below the data by factors of 2 to ten at $Q^2 = 4$ $(\mathrm{GeV/c})^2$, and the relativistic corrections make the agreement worse.[11] Similarly the charge form factor of ^3He is poorly described. Figure 3 shows one of the recent calculations[12] based on the best available Faddeev 3-body wave functions. When contributions from meson exchange (MEC) and isobars are included, there is improvement in the size and shape of the diffractive features, but the theory still falls below the data at the largest Q^2. This pattern of too-low predictions can also be seen in the inelastic data. In Fig. 4 the momentum space wave function $\psi^2(k)$ for nucleons in the deuteron extracted[13] from quasi elastic *ed* scattering lies considerably above the conventional 2-body wave functions above $k = 200$ MeV/c. Similarly for ^3He the Faddeev predictions[14,15] of the inclusive electron spectra at large Q^2 and small energy transfer (corresponding to large internal momentum k) are all smaller than the measurements[4] by factors of 2 or more.

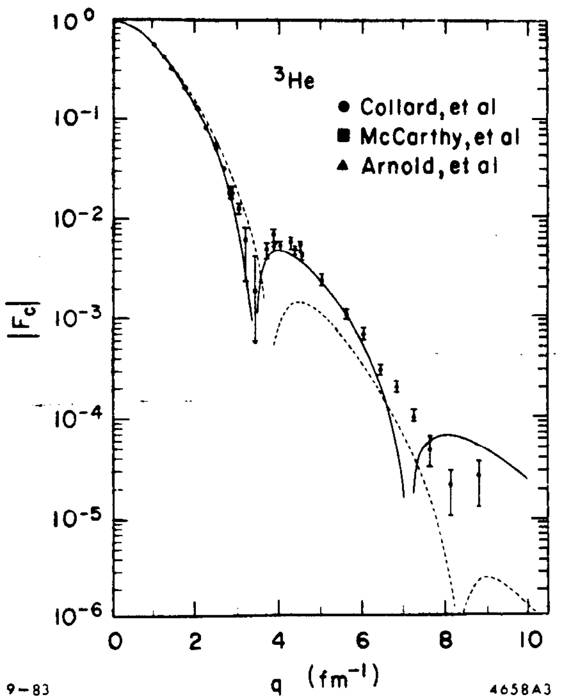

FIGURE 3. The charge form factor of ^3He taken from ref. 12. The dashed curve is the impulse approximation, the solid curve includes MEC.

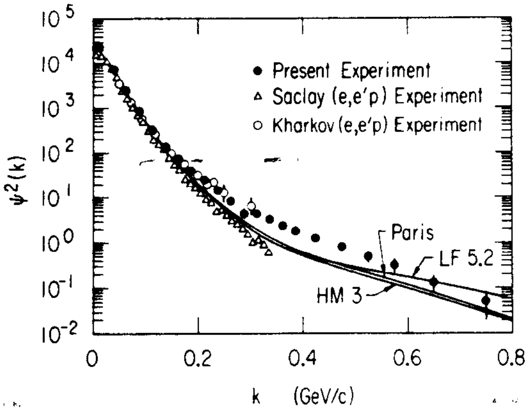

FIGURE 4. Experimental deuteron wave functions compared to three nonrelativistic models. The figure and the solid points are from ref. 13.

These deviations of the conventional models from the high Q^2 data have been interpreted to be possible due to various deficiencies of the models: not enough high momentum components in the wave functions; the need for inclusion of MEC and isobar contributions; and relativistic effects. Unfortunately the present status of the conventional models is far from satisfactory. We do not yet have a completely consistent relativistic treatment of few nucleon structure including meson and isobar currents. In some cases the addition of these terms seems to bring the theory closer to the data. However closer examination prompts us to proceed with caution. The *ad hoc* way the higher order terms are presently patched into the nonrelativistic theory is open to question.[11,18] The theoretical results also have a large sensitivity to a large number of unknown parameters (nucleon form factors, meson-nucleon couplings and form factors, relativistic effects).

It is also possible that what we are seeing is the slow breakdown of the conventional picture and the gradual emergence of the quark degrees of freedom. In the Q^2 range up to 4 $(\text{GeV/c})^2$ we are looking at a transition region where on the one hand nucleons become strongly overlapping at short distances and lose their identify, and on the other hand the quarks are moving in the long range region dominated by nonperturbative dynamics. In this dual region it is possible that both theoretical pictures will have some approximate validity, and that a major goal of our study ought to be to understand one description in terms of the other. To make progress in this program we need to continue to develop, if possible, a completely consistent conventional relativistic theory[16] so as to have a basis for identifying the breakdown and the possible emergence of quark effects. It is also essential to press on with more explicit QCD calculations[17–22] of cross sections including the nomalizations in addition to the predictions of asymptotic form factors.[7] Eventually from intercomparison of these competing models and the data we may begin to understand how the constituents of nuclear matter at short distance can best be described. Clearly what is needed for this program to succeed is extensive high quality data in this transition region. It is also essential to make comprehensive comparisons with all available structure function data, not just subsets of it. This leads to my third observation:

C. Much of the necessary electromagnetic structure function data on the nucleons[23] and the few body nuclei is poorly known or entirely missing. Of all the possible 24 single arm elastic and inelastic structure functions for the nucleons and $A \leq 4$ nuclei (G_E, and G_M, for nucleons, G_C, G_Q, and G_M for deuterium, F_C and F_M, for ^3He and ^3H, νW_2, W_1 for all) for $Q^2 \geq 1$ (GeV/c)^2, we have no information at all for eleven of them and in many cases the others are not well measured at large Q^2. This situation makes impossible the kind of comprehensive comparison necessary to narrow the theoretical choices. Consider the following cases:

Proton: In many processes the dominant contributions in the impulse approximation arise from terms proportional to G_{Mp}. At present for most purposes the error arising from the 2-3% error on G_{Mp} out to 4 (GeV/c)^2 is not the dominant uncertainty. However, eventually we will need to know G_{Mp} more precisely, especially as we move toward more detailed questions about the difference between on-shell and off-shell form factors and the extent of distortion of the free nucleons in the nuclear medium. G_{Ep} is poorly know.[24] The errors at $Q^2 = 2$ (GeV/c)^2 are ±20% and nothing is known above 3.8 (GeV/c)^2. The lack of knowledge of G_{Ep} is a serious problem for nuclear structure calculations in the transition region.

Neutron: The 5% uncertainty[6] in G_{Mn} out to 4 (GeV/c)^2 contributes to the overall uncertainty of many calculations. As with the proton, eventually we will need more accurate measurements of G_{Mn} as our tests of models become more refined. G_{En} is very poorly known,[25] partly because it is nearly zero. The present values extracted from elastic and quasi elastic *ed* scattering have experimental errors of 50% to 100%, and they are subject to large uncertainties from deuteron model dependence. There is no data above $Q^2 = 1.5$ (GeV/c)^2. This lack of knowledge is a major problem for few nucleon studies. In the deuteron $A(Q^2)$, for example, large differences are possible depending on which values for G_{En} are assumed.[11] G_{En} is also of high intrinsic interest because it tells about the charge distribution of the neutron. This we now believe to arise from a delicate balance between the charge on the $+2/3$ and the two $-1/2$ valence quarks and the cloud of ocean quarks resulting in a spacial distribution of charge that is not everywhere zero.[26] Measurements of G_{En} will provide important tests of nucleon structure.

Deuteron Elastic: The major experimental goals here are measurement of the magnetic form factor $B(Q^2)$ (or G_M) beyond[27] $Q^2 = 1$ (GeV/c)^2 and a separation of the charge G_C and quadrupole G_Q form factors. The G_M and G_C are each predicted in the impulse approximation[10,11] to have sharp diffractive features which get shifted or even totally obliterated when MEC[10] or 6-quark[18,20] contributions are included. A major advance in our understanding of the relevant degrees of freedom at short distances for two nucleons will be made when these functions are measured.

Deuteron Inelastic: Threshold electrodisintegration of the deuteron is already identified[28] as a sensitive place to see effects MEC, and this data[29] needs to be extended to Q^2 above 1 (GeV/c)^2 to see if the trends continue. In general a complete Rosenbluth separation of the longitudinal and transverse response functions from threshold out into the nucleon resonance region will be very useful for helping to identify the relevant scattering mechanisms.[30]

Helium and Tritium: Separation of the complete set F_C, F_M, νW_2, and W_1 in the 3-body nuclei over the whole kinematic domain accessible with high energy electrons is essential for progress in this field. We have already seen the rich information contained in F_{ch} and νW_2 for ^3He. The magnetic elastic form factors are especially important as they are predicted[12] to be very sensitive to many ingredients of the conventional models. At present nothing is known of ^3H above 0.3 (GeV/c)^2. Eventually ^3H and ^3He structure function data at large Q^2 will give powerful constraints as the models are required to simultaneously reproduce the diffractive features in all the structure functions in a consistent picture.

In addition to the single arm structure functions, we eventually will need measurements of as many of the coincidence cross sections as possible. Of particular interest are measurements of the type $(e, e'p)$ which can be interpreted in terms of the spectral functions[15] (convolutions of the initial and final state wave functions). The present measurements[31] are limited to nucleon momentum $k \leq$ 300-400 MeV/c and separation energy $E_s \leq$ 60-80 MeV primarily by the background of accidental coincidences. For extension of these experiments it is essential to have high-intensity high-duty electron beams in the GeV region.

3. FUTURE EXPERIMENTS

There are two recent developments in the U.S. that promise to help provide the missing data outlined above. First is the recent approval and appropriation of funds for construction of a new injector at SLAC. The other is a recent recommendation[8] by a DOE-NSF review panel for construction of a new high duty 4 GeV electron machine in Newport News, Virginia, as proposed by the South Eastern University Research Association (SURA).

The SLAC injector is a project originated by the American University Group at SLAC to add a new electron gun and injector near the downstream end of the two mile long SLAC linac to provide high intensity (35 μA average), good quality beams in the energy range 0.5 to approximately 5 GeV. The construction project is now getting underway (October

1983), and we expect to have beam for testing in early 1985. This new beam will be used for a program of nuclear structure measurements using the existing facilities of SLAC End Station A. The primary emphasis will be on elastic and inelastic electron scattering in the $A \leq 4$ nuclei. These experiments will take full advantage of the high energy and beam current but do not need high duty factor. An example of the extension in sensitivity is shown in Fig. 5 where the Q^2 range accessible for a measurement of the deuteron $B(Q^2)$ is plotted. In this case the elastically scattered electrons will be measured in coincidence with the recoil nuclei. Similar extension of the separation of F_C and F_M for ^3He and ^3H will be possible as well as separation of νW_2 and W_1 in all these nuclei.

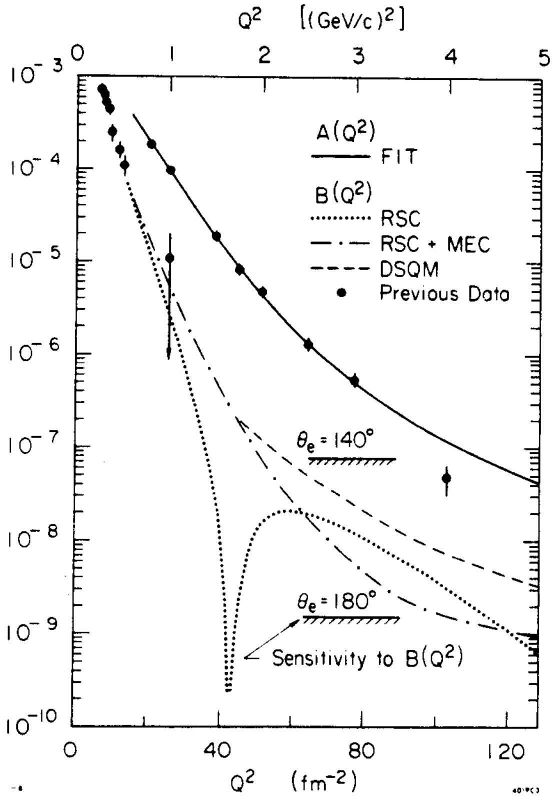

FIGURE 5. Sensitivity of experiments proposed with the new injector at SLAC for measurements of the deuteron $B(Q^2)$.

In addition to standard scattering measurements we are particularly interested in the possibility to use polarized electrons to separate elastic form factors.[32] In the case of scattering longitudinally polarized electrons from nucleons, the polarization transferred to the nucleons depends upon the form factors:

$$I_0 P_x = -2\left[\tau(1+\tau)\right]^{1/2} G_M G_E \tan\left(\frac{1}{2}\theta\right) \quad ; \quad \tau = \frac{Q^2}{4m^2}$$

$$I_0 P_z = 2\tau\left\{(1+\tau)\left[1+\sin^2\left(\frac{1}{2}\theta\right)\right]\right\}^{1/2} G_M^2 \sec\left(\frac{1}{2}\theta\right)\tan\left(\frac{1}{2}\theta\right)$$

A measurement of the recoil nucleon polarization offers a new experimental method in addition to the Rosenbluth method to separate G_E from G_M. It appears feasible to make recoil neutron polarization analyzer/detectors based upon elastic *np* scattering with efficiency adequate to make measurements of G_{En} in the Q^2 range 0.5 to perhaps 2 (GeV/c)^2. A similar technique using *pp* scattering could be used to improve the knowledge of G_{Ep} above 2 (GeV/c)^2. It should be noted that for the neutron a measurement of P_x is a direct signature for G_{En} that can be made in a ratio experiment (up-down asymmetry) completely independent of models for deuteron wave functions and measurements of neutron detection efficiencies or any absolute counting rates. Measurement of G_{En} for any $Q^2 > 0$ would be extremely helpful, and experimenters at low and medium energy electron facilities should explore the possibilities for such experiments, perhaps using elastic neutron-helium scattering for the analyzer.

In the case of elastic *ed* scattering with longitudinal beam polarization *a*, the cross section for *ed* scattering followed by a second analyzing reaction is:

$$\begin{aligned}\frac{d^2\sigma}{d\Omega d\Omega_2} = \left.\frac{d^2\sigma}{d\Omega d\Omega_2}\right|_0 \Big\{1 &+ \frac{3}{2}\, a p_x A_y \sin\phi_2 + \frac{1}{2} p_{zz} A_{zz} \\ &+ \frac{2}{3}\, p_{xz} A_{xz} \cos\phi_2 \\ &+ \frac{1}{6}\, (p_{xx} - p_{yy})(A_{xx} - A_{yy}) \cos 2\phi_2 \Big\}\end{aligned}$$

The term proportional to p_x, the vector polarization transferred to the recoil deuterons (perpendicular to the recoil momentum and in the scattering plane), is present only when the beam is polarized. p_x depends upon different combinations of G_C and G_Q than does the cross section, and it could be measured in an up-down asymmetry in a second scattering provided the analyzing power A_y $(2/\sqrt{3}\, iT_{11})$ is known. If a recoil polarization analyzer were available with full azimuthal symmetry, as for example using elastic scattering from carbon with track reconstruction before and after the scattering, then with sufficiently accurate data a Fourier decomposition would allow separation of the ϕ_2 dependent terms. In particular the ratio of the amplitude of the $\sin\phi_2$ and $\cos\phi_2$ components would yield:

$$\frac{p_x}{p_{xz}} = \frac{4}{3}\, [\eta(1+\eta)]^{1/2}\, \frac{M_d}{E+E'} \left(\frac{G_C}{\eta G_Q} + \frac{1}{3}\right) \;, \text{ where } \eta = \frac{Q^2}{4M_d^2} \;.$$

Before such measurements can be undertaken, it is essential to have more precise and extensive measurements of the analyzing powers for a suitable reaction. There are now underway an important series of measurements[33] at Saturne in Saclay on *dp* and *dC* scattering that hopefully will yield the required analyzing powers and make possible and eventual separation of G_C and G_Q.

The low duty factor of SLAC (10^{-4}) will not allow performance of any inelastic coincidence experiments, such as $(e, e'p)$. For these we eagerly await the development over the next few years of high duty electron facilities. This will open up a vast new area for experimental exploration of the inelastic final states and provide much new evidence for discussion at future few body conferences.

4. WATCH FOR SURPRISES

I conclude with a reminder that we must continue to be awake for surprises that may come along to modify our points of view and perhaps reorder the priorities of our experimental programs. A recent example is the discovery by the European Muon Collaboration at CERN,[34] and confirmed by old SLAC data,[35] that deep inelastic scattering from the quarks in deuterium is not the same as in iron. This discovery has sent big ripples across the boundary between nuclear and particle physics. The data indicate that the quark distributions are distorted when nucleons are embedded in a large nucleus compared to those in (nearly) free nucleons. This effect provides an important new signature for quark degrees of freedom in nuclei.

There have been several recent theoretical papers suggesting possible mechanisms for the distortion of quark distributions in nuclei. These include nucleon overlap into multiquark bags,[36] the presence of quasi pions[37] and isobars[38] in nuclei, and changes in the effective mass and radius of nucleons found in nuclei.[39] In the region $x \leq 0.2$ there are apparently effects due to photon shadowing, and the region $x > 1$ (forbidden to free nucleons) will be the place to look for cumulative effects.[21,22,40]

5. CONCLUSION

The field of high energy electron scattering from nuclear targets is at the threshold of an exciting new era. High energy electron experiments are particularly good ways to look for QCD effects in nuclear systems because they provide clean measurements of the charges and currents carried by the quarks in nuclei. We look forward in the near future to much more data that that will provide important new tests of our understanding of the underlying quark degrees of freedom in nuclei.

REFERENCES

1. R. G. Arnold, et al., Phys. Rev. Lett. **35** (1975) 776.
2. W. P. Schütz, et al., Phys. Rev. Lett. **38** (1977) 259.
3. R. G. Arnold, et al., Phys. Rev. Lett. **40** (1978) 1429.
4. D. Day, et al., Phys. Rev. Lett. **43** (1979) 1143.
5. S. Rock, et al., Phys. Rev. C **26** (1982) 1592.
6. S. Rock, et al., Phys. Rev. Lett. **49** (1982) 1139.
7. S. Brodsky and B. Chertok, Phys. Rev. D **14** (1976) 3003.
8. DOE/NSF Nuclear Science Advisory Committee, "Report of the Panel on Electron Accelerator Facilities," DOE/ER-0164 (April 1983).

9. E. D. Bloom, F. J. Gilman, Phys. Rev. D **4** (1971) 2901;
G. Miller, et al., Phys. Rev. D **5** (1972) 528.
10. M. Gari and H. Hyuga, Nucl. Phys **A264** (1976) 409.
11. R. G. Arnold, C. E. Carlson, and F. Gross, Phys. Rev. C **21** (1980) 1426;
M. J. Zuilhof, and J. A. Tjon, Phys. Rev. C **24** (1981) 736.
12. H. Hadjimichael, B. Goulard, R. Bornais, Phys. Rev. C **27** (1983) 831.
13. P. Bosted, et al., Phys. Rev. Lett. **49** (1982) 1380.
14. I. Sick, D. Day, J. S. McCarthy, Phys. Rev. Lett **45** (1980) 871.
15. H. Meir-Hajduk, et al., Nucl. Phys. **A395** (1983) 332.
16. J. L. Friar, Proceedings of International Conference on Nuclear Physics with Electromagnetic Interactions, Mainz, eds., H. Arenhövel and D. Drechsel, (1979) 445; Phys. Rev. **C22** (1980) 796.
17. S. J. Brodsky, Tao Huang, and G. P. Lepage, SLAC-PUB-2868, published in Springer Tracts in Modern Physics, Vol. 100, "Quarks and Nuclear Forces," ed., D. Fries and B. Zutnitz (1982);
S. J. Brodsky and J. R. Hiller, Phys. Rev. C **28** (1983) 475;
S. J. Brodsky, Chueng-Ryong Ji, and G. P. Lepage, Phys. Rev. Lett. **51** (1983) 83.
18. A. P. Kobyshikin, Sov. J. Nucl. Phys. **28** (1978) 252.
19. M. Beyer, D. Drechsel and M. M. Giannini, Phys. Lett. **122B** (1983) 1.
20. L. S. Kisslinger, Phys. Lett. **112B** (1982) 307.
21. L. L. Frankfurt, M. I. Strikman, Phys. Rep. **76** (1981) 217.
22. H. J. Pirner, J. P. Vary, Phys. Rev. Lett. **46** (1981) 1326.
23. G. Höhler, et al., Nucl. Phys. **B114** (1976) 505.
24. J. Litt, et al., Phys. Lett. **31B** (1970) 40.
25. S. Galster, et al., Nucl. Phys. **B32** (1971) 221.
26. A. W. Thomas, S. Théberge, and G. A. Miller, Phys. Rev. D **24** (1981) 216.
27. B. Frois, Saclay, invited paper III.6, at this conference.
28. J. Hockert, et al., Nucl. Phys. **A217** (1973) 14;
W. Leidemann and H. Arenhövel, Nucl. Phys. **A393** (1983) 385.
29. M. Bernheim, et al., Phys. Rev. Lett. **46** (1981) 402.
30. W. Fabian and H. Arenhövel, Nucl. Phys. **A314** (1979) 253.
31. M. Bernheim, et al., Nucl. Phys. **A365** (1981) 349;
E. Jans, et al., Phys. Rev. Lett. **49** (1982) 974.
32. R. G. Arnold, C. E. Carlson, F. Gross, Phys. Rev. C **23** (1981) 363.
33. J. Arvieux, Saclay, private communication and Discussion Section DS4, this conference.
34. J. J. Ambert, et al., Phys. Lett. **123B** (1983) 275.
35. A. Bodek, et al., Phys. Rev. Lett. **50** (1983); Phys. Rev. Lett. **51** (1983) 534.

36. R. L. Jaffe, Phys. Rev. Lett **50** (1983) 228;

C. E. Carlson and T. J. Havens, Phys. Rev. Lett. **51** (1983) 261.

37. C. H. Llewellyn Smith, Phys. Lett. **128B** (1983) 107;

M. Ericson and A. W. Thomas, Phys. Lett. **128B** (1983) 112;

E. L. Berger, F. Coester, R. B. Wiringa, Argonne Preprint ANL-HEP-PR-83-24 (June 1983).

38. J. Szwed, Phys. Lett. **128B** (1983) 245.

39. F. E. Close, R. G. Roberts, and G. G. Ross, Rutherford Laboratory Preprint RL-83-051 (1983).

L. L. Frankfurt and M. I. Strikman, Leningrad Preprint (1983) (to be published in Physics Letters).

40. L. L. Frankfurt and M. I. Strikman, Phys. Lett. **114B** (1982) 345;

A. M. Baldin, Dubna, presentation at this conference.