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- [ ] Front End
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- [X] Nuclear Physics
- [ ] RF
- [ ] Safety and Health Physics
- [ ] Schedule
- [ ] SRF
- [ ] Test Results
- [ ] Vacuum
- [ ] Other

ABSTRACT

We analyze the possibly of doing parity violation measurements using the CEBAF HRS spectrometer pair. In particular we examine possible measurements of elastic scattering from ^{4}He and H and quasielastic scattering from D. Elastic scattering from ^{4}He provides a measure of the electroweak coupling constant $\sin^2\theta_W$. We suggest measuring three Q^2 points on ^{4}He which will yield a statistical error of 2% in $\sin^2\theta_W$. The Q^2 dependance provides a test of the model assumptions. Elastic H and quasielastic D scattering have differing sensitives to the elastic form factor of the nucleon and its strange quark content. We suggest measuring five Q^2 points on these nuclei with 5% statistics per point. These experiments are feasible with the above accuracies provided that we can reach the same level of statistical uncertainty as was obtained in the recent Bates measurements by Souder et al.. Our analysis shows that for forward angle electron scatteriang the rates are favorable and precise measurements can be done in a reasonable amount of beam time.

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Electroweak Parity Violation Measurements Using the CEBAF HRS Spectrometer Pair

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Introduction

Measurement of the parity violating asymmetry in electron scattering is an important tool for understanding the electroweak coupling of photons to quarks. Determinations of the weak mixing angle, $\sin^2\theta_W$, via electron scattering have been made, both from deep inelastic scattering and from T=0, J=0 elastic scattering. However the statistical accuracy of the current measurements is somewhat limited. The deep inelastic scattering measurements from Prescott *et al.*[1] give a value of $\sin^2\theta_W = 0.224 \pm 0.020$, while Souder's measurement[2] from elastic scattering on ^{12}C give a value of $0.204 \pm 0.048 \pm 0.014$. Both these measurements are in agreement with the accepted value[3] of 0.2259 ± 0.0046. The various published measurements of $\sin^2\theta_W$ are sensitive to different aspects of the standard model. In addition to the above measurements, quasielastic measurements on ^9Be have also been performed via electron scattering at Mainz.[4]

Beyond tests of the standard model, parity violating measurements can yield a wealth of additional information about the electroweak current. In general there are three parity violating interference response functions which can be separated by measurements made at three electron scattering angles. Electron-hydrogen scattering proposals have been made at both MIT-BATES[5] and CEBAF[6] to obtain constraints on the strange quark content as well as the electric form factor of the neutron [7].

We address the possibility of doing some initial parity violation measurements using the two identical Hall A spectrometers at CEBAF. Because of rate considerations only forward angle measurements are presently being considered using these spectrometers. These measurements will need to be complemented by additional measurements in Hall C using specialized large acceptance instruments. The two Hall A spectrometers will be placed at the minimum scattering angle of 12.5°, and will have sufficient hardware resolution (approximately 10^{-3} without software corrections) to resolve the states of interest. Since the spectrometers are part of the initial complement of equipment and the analog detectors needed for parity violation measurements are relatively inexpensive, the primary cost and effort will go into developing a good understanding of the systematic errors and the necessary beamline instrumentation. This instrumentation is also required for other parts of the Hall A program using polarized beams.

We have analyzed two possible experiments for which high precision measurements can be taken in a reasonable amount of time. The first experiment involves measurements of $\sin^2\theta_W$ via elastic electron scattering from ^{4}He. The second experiment involves measurements of the weak interference amplitude from elastic scattering from hydrogen and quasielastic scattering from deuterium.

Elastic scattering from ^{4}He

Elastic scattering from ^{4}He yields the same type of information as elastic scattering measurements on ^{12}C undertaken at Bates by Souder *et al.*[2]. Parity violation experiments measure an asymmetry between the two longitudinal helicity states of the electron beam:

$$\mathcal{A} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$

where $\sigma_+(\sigma_-)$ denotes the cross sections for scattering from positive (negative) helicity electrons. In the case of a T=0, J=0 nucleus, the asymmetry in the Weinberg model is given by[8]

$$\mathcal{A} = \frac{G_F}{\sqrt{2}\pi\alpha}Q^2\sin^2\theta_W$$

where Q^2 is the four-momentum transfer squared, $G_F = 1.16637(2)\times10^{-5}\ (\mathrm{GeV/c})^{-2}$ is the Fermi coupling constant,[3] and α is the fine structure constant. This result is independent of the nuclear structure assuming no isovector admixture in the ground state and strong isospin for the weak vector current. This result is somewhat model dependent as shown by the work of Beck[9], where assuming an SU(3) quark model and allowing an admixture of strange quarks in the ground state he obtains

$$\mathcal{A} = \frac{G_F}{\sqrt{2}\pi\alpha}Q^2\sin^2\theta_W\left[1 + \frac{AF_s}{4ZF_{ch}}\right]$$

where A and Z are the atomic mass number and charge respectively, F_{ch} is the charge form factor of ^{4}He, and F_s is the strange quark form factor which is constrained to go to zero as Q^2 goes to zero. The amount of strange quark admixture in the ground state is not well constrained by present measurements. Measurements of the asymmetry at several values of Q^2 can be used to extract $\sin^2\theta_W$ by extrapolating to $Q^2 = 0$. The Q^2 dependence of $\mathcal{A}$ can be used to test the model assumptions.

For example, in the standard model, assuming no strange quark admixture and assuming a pure isovector ground state, $\mathcal{A}/Q^2$ should be a constant independent of the nuclear structure. Isovector contamination of the ^{4}He ground state is expected to be small.[10] The primary advantage of using ^{4}He rather than ^{12}C is that the elastic form factor falls more slowly in ^{4}He. This increases the optimum Q^2, allowing one to extract a larger asymmetry. Figure 1a shows the cross sectional variation as a function of Q^2. The charge form factor of ^{4}He is obtained from a fit to a Gaussian distribution by Frosch[11] *et al.* using an RMS radius of 1.68 fm. Figure 1b shows the asymmetry assuming no strange quark admixture. The plotted values are for point cross sections and asymmetries at a 12.5° scattering angle. Since these values vary rapidly with scattering angle we have also evaluated the effect of the finite acceptances of the Hall A spectrometers in Table 1. Q^2 changes by ±23% over the acceptances. Typically the difference between the average and central values of the cross section and asymmetry are on the order of 10% each. Figure 1c shows the figure-of-merit, defined as $< \mathcal{A}^2 d\sigma/d\Omega >$ as a function of Q^2 including finite acceptance effects. The figure-of-merit peaks at a beam energy of approximately 0.95 GeV. The energy range over which an initial set of measurements might be made is from 0.45 to 1.55 GeV. This represents the energies at which the figure-of-merit has fallen by a factor of two from its maximum value. The equivalent Q^2 range is from 0.01 to 0.11 $(\mathrm{GeV/c})^2$. It appears reasonable to measure three points at beam energies of 0.45, 0.95, and 1.55 GeV. If the same statistical precision is desired for all three points, the middle point will require half the counting time than for either of the other two points. If one can control the systematic errors to 2×10^{-8} as Souder's experiment, the systematic error will be approximately 3.3% at the lowest Q^2 point and 0.3% at the highest Q^2 point. The ability to control the systematic errors will affect the optimum Q^2 range of this experiment.

In order to obtain a time estimate we have made the following assumptions: an average beam current of 100 μA, a beam helicity polarization of 80%, a target thickness of 2.0 gm/cm^2, and a spectrometer solid angle of 8.0 msr (16.0 msr total for both spectrometers). With these assumptions a 400W cryogenic gas target is required. In addition, improvement of the beam polarization above the demonstrated 50% polarization is required. A beam polarization of 80% appears to be a reasonable goal in light of current research and development of chalcopyrite sources. With these assumptions a 3% measurement of the asymmetry can be made in 10 days for the central point or approximately 50 days for all three points. This should result in an overall statistical error in $\sin^2 \theta_W$ of 1.7%. These estimates do not include radiative corrections which reduce the cross sections by about 30% and increase the error in $\sin^2 \theta_W$ to 3.4% per point or 2% overall for the same 50 day running period. The production runs can be broken into three runs of 10, 20, and 20 days each.

Table 1
^{4}He

E_o GeV	θ deg	Q^2 GeV/c^2	σ μb/sr	$<\sigma>$ μb/sr	$\mathcal{A}$ 10^{-6}	$<\mathcal{A}>$ 10^{-6}	FOM $<\sigma\mathcal{A}^2>$	Rate Counts/sec	Error %
0.25	12.5	0.003	2169.354	2285.137	0.245	0.236	81.5	0.660E+10	7.01
0.35	12.5	0.006	1032.849	1090.701	0.479	0.462	148.8	0.315E+10	5.19
0.45	12.5	0.010	569.938	603.950	0.792	0.761	224.0	0.174E+10	4.23
0.55	12.5	0.014	340.206	362.149	1.182	1.134	298.0	0.105E+10	3.67
0.65	12.5	0.020	212.330	227.330	1.650	1.579	362.6	0.657E+09	3.32
0.75	12.5	0.027	135.912	146.558	2.195	2.094	411.2	0.423E+09	3.12
0.85	12.5	0.034	88.162	95.901	2.818	2.678	440.2	0.277E+09	3.02
0.95	12.5	0.043	57.493	63.203	3.518	3.330	448.5	0.183E+09	2.99
1.05	12.5	0.052	37.485	41.731	4.295	4.047	437.5	0.121E+09	3.03
1.15	12.5	0.062	24.337	27.502	5.148	4.828	410.3	0.794E+08	3.12
1.25	12.5	0.073	15.687	18.041	6.079	5.670	371.2	0.521E+08	3.29
1.35	12.5	0.086	10.015	11.758	7.086	6.571	324.9	0.340E+08	3.51
1.45	12.5	0.099	6.322	7.602	8.169	7.527	275.7	0.220E+08	3.81
1.55	12.5	0.113	3.940	4.871	9.329	8.538	227.2	0.141E+08	4.20
1.65	12.5	0.128	2.422	3.091	10.565	9.599	182.2	0.893E+07	4.69
1.75	12.5	0.144	1.467	1.941	11.877	10.707	142.4	0.561E+07	5.30
1.85	12.5	0.160	0.875	1.206	13.265	11.860	108.6	0.348E+07	6.07
1.95	12.5	0.178	0.513	0.741	14.729	13.055	80.9	0.214E+07	7.04

Table 1. Cross sections and rates for ^{4}He(e,e$'$) parity violation measurements assuming 100 μA beam, 2.0gm/cm^2 target, and a 16 msr total acceptance for the HRS spectrometer pair. Error shown is the statistical error for a 240 hour measurement per point. Three points at 0.45, 0.95, and 1.55 GeV are proposed.

Scattering from Hydrogen and Deuterium Targets

For eN elastic scattering three weak form factors contribute to the asymmetry [12]

$$\mathcal{A}_{exp} = -\frac{G_F Q^2}{\sqrt{2}\pi\alpha\xi}\left[\varepsilon G_E^\gamma G_E^Z + \tau G_M^\gamma G_M^Z - \frac{1}{2}(1-4\sin^2\theta_W)(1-\varepsilon^2)^{\frac{1}{2}}\sqrt{\tau(1+\tau)}G_M^\gamma G_A^Z\right]$$

where $\xi = \varepsilon(G_E^\gamma)^2 + \tau(G_M^\gamma)^2$, ε is the longitudinal photon polarization, τ is equal to $Q^2/4M^2$, G_E^γ and G_M^γ denote the ordinary electromagnetic form factors of the nucleon, G_E^Z and G_M^Z are the analogous weak form factors and G_A^Z is the axial vector form factor.

Beck,[9] assuming the standard model, strong isospin for the proton and the neutron, and a (u,d,s) quark model, finds the following relationship between the weak currents and the electromagnetic currents[12]

$$G_{E_p}^Z(Q^2) = \left[\frac{1}{4} - \sin^2\theta_W\right] G_{E_p}^\gamma(Q^2) - \frac{1}{4}G_{E_n}^\gamma(Q^2) - \frac{1}{4}G_{E_p}^s(Q^2)$$

$$G_{M_p}^Z(Q^2) = \left[\frac{1}{4} - \sin^2\theta_W\right] G_{M_p}^\gamma(Q^2) - \frac{1}{4}G_{M_n}^\gamma(Q^2) - \frac{1}{4}G_{M_p}^s(Q^2)$$

with an analogous relationship for the weak neutron form factor. In the above equation G^S denotes the strange quark contribution. The results are sensitive to the electric form factor of the neutron which is not well known at present, and to the strange quark content of the proton.

For deuterium we make the quasielastic approximation[9]:

$$\mathcal{A} = \frac{Z\mathcal{A}^p\sigma_0^p + N\mathcal{A}^n\sigma_0^n}{Z\sigma_0^p + N\sigma_0^n}$$

where $\mathcal{A}^p$ and $\mathcal{A}^n$ are the proton and neutron asymmetries and σ_0^p and σ_0^p are the unpolarized proton and neutron cross sections, respectively.

In general one can separate the three weak form factors by performing a generalized Rosenbluth separation at three scattering angles. In practice, the small rates at large angles require the construction of large acceptance devices to perform an experiment in a reasonable amount of time.

Here we analyze a possible experiment in the forward angle sector where the rates are high. In this sector the axial vector contribution is minimal and one is sensitive to the strange quark admixture and the electric form factor of the neutron. Quasifree deuterium scattering has a different selectivity than elastic proton scattering, with deuterium scattering being more sensitive to the electric neutron form factor and less sensitive to the strange magnetic form factor due to the isospin selection rules.

Another concern with deuterium scattering is the presence of other open channels in the quasifree region. The effective Fermi momentum for deuterium is small however, and the quasielastic channel can be separated from the quasifree pion channel, which is the other major competing mechanism.

The cross section, asymmetry, and figures-of-merit are shown in Figures 2 through 5 for two kinematical cases: Figures 2 and 3 show hydrogen and deuterium scattering at the minimum scattering angle of 12.5 degrees for different beam energies. Figures 4 and 5 show the results for scattering at a fixed beam energy of 4.35 GeV at various scattering angles. Due to kinematical recoil the final electron energy is below 4 GeV for an incident electron energy of 4.35 GeV and θ of 12.5 degrees. This corresponds to the maximum of the figure-of-merit at the minimum obtainable scattering angle. Measurements can therefore be made up to a Q^2 of 0.95 GeV/c^2 before reaching the design limit of the spectrometers. To reach higher Q^2 values one can fix the incident electron energy at 4.35 GeV and increase the scattering angle. The general behavior is similar for deuterium and hydrogen, with the figures-of-merit varying by a factor of two over the range 0.27 $(\mathrm{GeV/c})^2 < Q^2 < 1.3$ $(\mathrm{GeV/c})^2$. A reasonable goal might be to make five measurements in this range ($Q^2 = 0.27, 0.52, 0.81, 1.05, 1.30$ $(\mathrm{GeV/c})^2$).

The asymmetry of deuterium is somewhat larger than that of hydrogen and the density of liquid deuterium is 2.3 times that of liquid hydrogen. Although deuterium is denser than hydrogen, the energy deposited in two identical cells (one containing liquid deuterium and the other containing liquid hydrogen) will be nearly the same. The net result is that an experiment on deuterium will take approximately one third the amount of time as one on hydrogen for the same statistical precision.

Rates for hydrogen and deuterium scattering are shown in Tables 2 and 3. These rates assume a 100 μA beam with 80% polarization and a 1.0 (2.3) g/cm^2 hydrogen (deuterium) target. Errors shown in the tables assume 270 (90) hours for hydrogen (deuterium), with errors averaging $3.5 \sim 5.0\%$ per point. Corrections for radiative losses will increase these statistical errors to $4.5 \sim 5.7\%$ per point. Logically runs on deuterium and hydrogen should be done at the same time with each kinematics requiring a 15 day run. The total time required for measuring five points is 75 days. These time estimates of course do not include time required for calibration and understanding the systematic errors.

Summary

We have analyzed two possible parity violation experiments that can be performed with the initial complement of equipment in Hall A. Both experiments appear to be feasible and emphasize different aspects of the electroweak interaction. The ^{4}He experiment provides a test of the standard model while the H/D experiment measures the weak form factor over a significant range of Q^2. Depending on taste, either experiment could be a suitable choice for a first parity violation experiment at CEBAF. Both experiments represent a significant advance in statistical accuracy and kinematical range compared to previous parity violating electron scattering experiments. In our analysis we have assumed that a beam polarization of 80% will be obtainable by the time these experiments are performed. High beam polarizations are necessary to carry out an extended program of measurements due to the small size of the asymmetries. High powered cryogenic gas targets on the order of 400W are also necessary.

Clearly the most serious problem is the question of whether one can control the systematic errors to a level comparable to the statistical precision obtainable at CEBAF using the Hall A HRS spectrometer pair. In principal this goal appears achievable if we can control systematics to the same level as was reported in the recent Bates experiment[2]. In that experiment Souder *et al.* reported a systematic error of 0.02 ppm. Given the improved emittance and energy spread of the CEBAF beam and the potentially more stable performance of the continuous duty factor beam one should be able to reach similar accuracies at CEBAF. This will allow measurements at the 0.4 to 4.0% level on ^{4}He and a fraction of a percent on H and D. An energetic program of several years duration will have to be undertaken to understand the detector and beam performance before these experiments can be scheduled.

It is beyond the scope of this paper to define the necessary instrumentation required for this program. It is clear that very sophisticated beamline instrumentation will be required to define the beam parameters. We have made a step in this direction in a separate memo [13] where we discuss the use of a beamline chicane in Hall A. The chicane will be used in conjunction with a laser polarimeter to define the polarization of the beam to about 1% accuracy. It will also be used to

determine the absolute energy of the beam to about the 10^{-4} level and the beam orientation on target to better than 0.01 mr. Synchrotron radiation in the chicane can be used to determine the relative beam currents to a very high precision.

An important issue is whether a parity violation experiment can co-exist with the existing program in Hall A. We believe the answer to this question is a qualified "yes". Initial work will emphasize understanding the central beam parameters. Much of this work is necessary to carry out other aspects of the Hall A program, such as polarization transfer studies on D and ^{16}O which make demanding requirements on knowledge of the polarization, energy and orientation of the beam. Clearly the demands of the parity violation program will serve to improve knowledge of the beam parameters which are also needed for other experiments. As the parity violation study proceeds, increasing demand will be made on beam time dedicated for analyses of systematic errors. The initial production runs can be limited to a single energy and will require no more than 15 days of running time and can be limited in facility impact to one or two months in the initial year of running. The detectors needed for parity violation measurements could be made interchangeable with existing Čerenkov detectors. The Hall A electronics can either be turned off and left in place, or could conceivably be used as a parasitic monitor of the beam profile in the spectrometer.

Ultimately, given the difficulty of the experiments and the time committment required, the fundamental issue will be whether a group of people will dedicate themselves to carrying such a set of measurements. We believe the proposed experiments merit such an undertaking.

Table 2
Hydrogen

E_o GeV	θ deg	Q^2 GeV/c^2	σ μb/sr	$<\sigma>$ μb/sr	$\mathcal{A}$ 10^{-6}	$<\mathcal{A}>$ 10^{-6}	FOM $<\sigma\mathcal{A}^2>$	Rate Counts/sec	Error %
2.45	12.5	0.268	2.379	2.590	−6.981	−6.524	70.5	0.150E+08	5.02
3.45	12.5	0.519	0.598	0.669	−18.537	−17.133	125.7	0.387E+07	3.76
4.35	12.5	0.808	0.192	0.221	−34.561	−31.748	142.6	0.128E+07	3.53
4.35	14.5	1.050	0.065	0.073	−49.670	−46.656	101.1	0.419E+06	4.20
4.35	16.4	1.295	0.025	0.028	−65.878	−62.802	70.2	0.161E+06	5.03

Table 2. Kinematics and rates for H measurement. Rates assume a 100μA beam and 80% beam polarization, 16 msr total acceptance for the HRS spectrometer pair and a 1.0 gm/cm^2 target. Running times are 270 hours per point.

Table 3
Deuterium

E_o GeV	θ deg	Q^2 GeV/c^2	σ μb/sr	$<\sigma>$ μb/sr	$\mathcal{A}$ 10^{-6}	$<\mathcal{A}>$ 10^{-6}	FOM $<\sigma\mathcal{A}^2>$	Rate Counts/sec	Error %
2.45	12.5	0.268	2.816	3.049	−10.374	−9.720	184.4	0.202E+08	5.03
3.45	12.5	0.519	0.756	0.841	−26.940	−25.008	336.5	0.556E+07	3.72
4.35	12.5	0.808	0.253	0.289	−49.134	−45.349	380.6	0.191E+07	3.50
4.35	14.5	1.050	0.087	0.097	−69.642	−65.630	267.9	0.643E+06	4.17
4.35	16.4	1.295	0.035	0.038	−91.398	−87.332	185.0	0.251E+06	5.02

Table 3. Kinematics and rates for D measurement. Rates assume a 100μA beam and 80% beam polarization, 16 msr total acceptance for the HRS spectrometer pair and a 2.3 gm/cm^2 target. Running times are 90 hours per point.

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Figure 1a

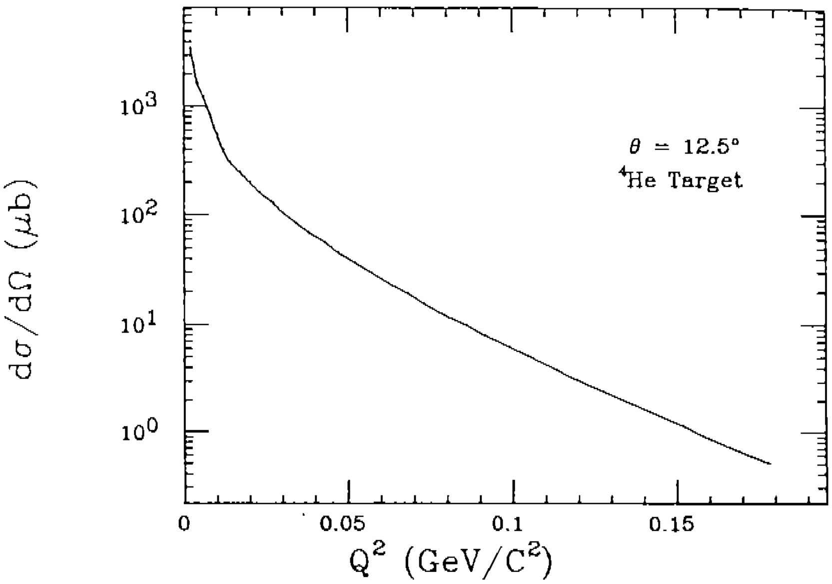

Figure 1b

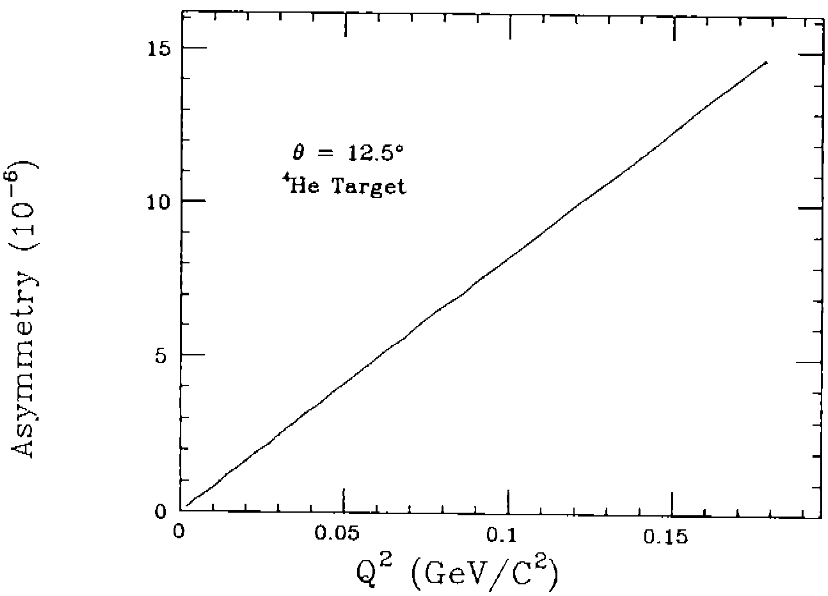

Figure 1c

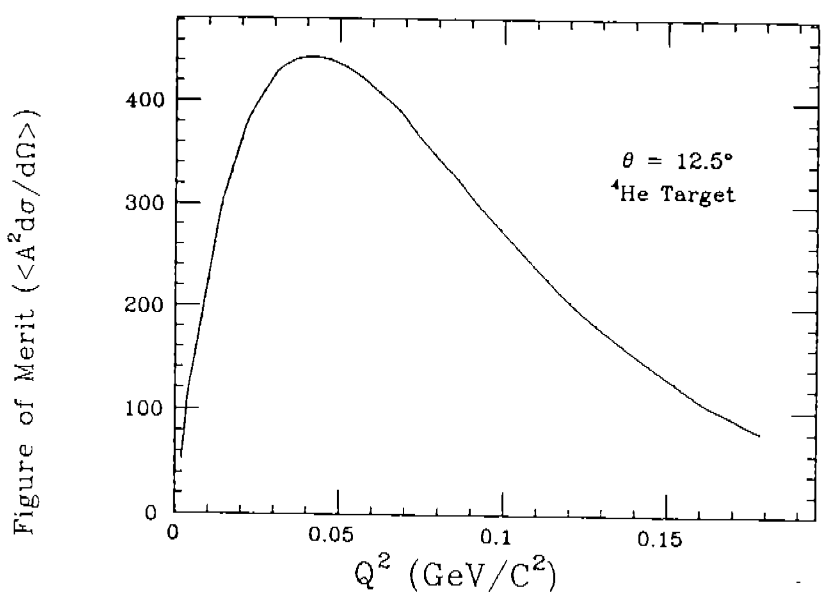

Figure 2a

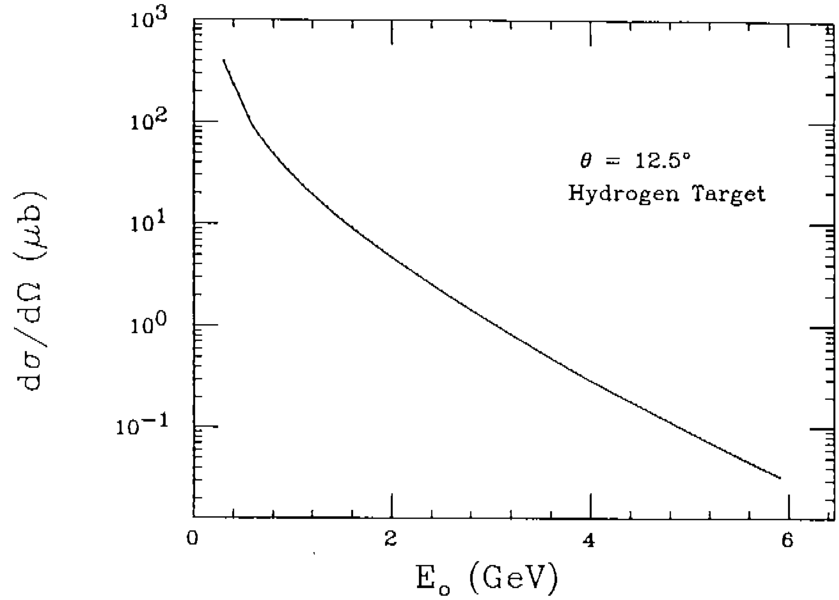

Figure 2b

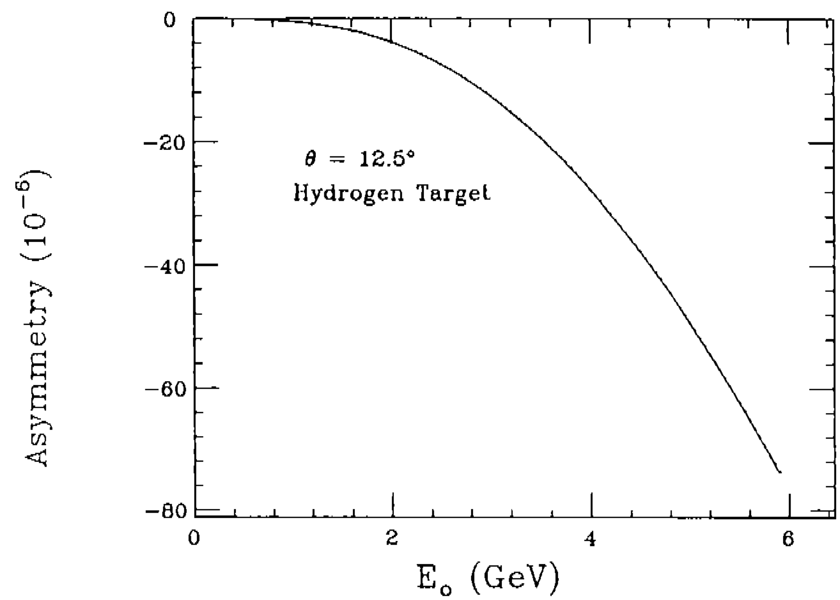

Figure 2c

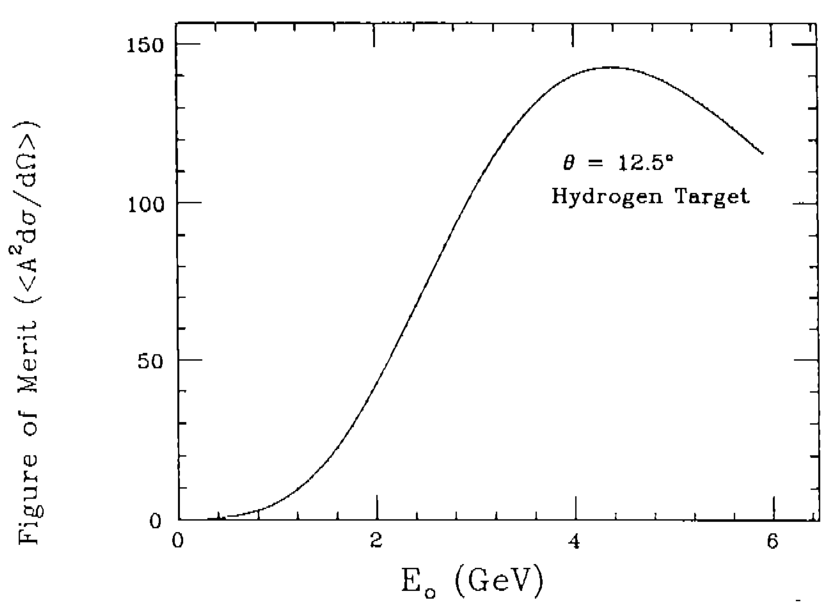

Figure 3a

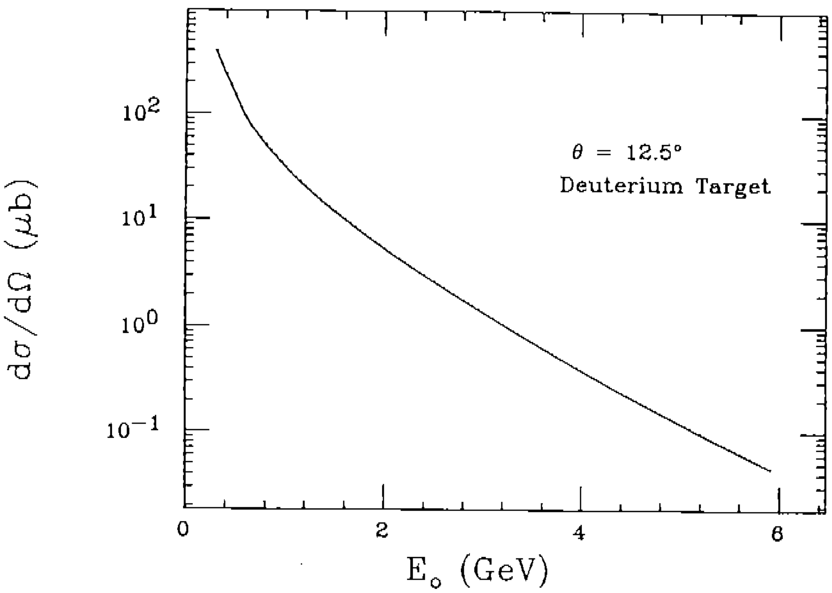

Figure 3b

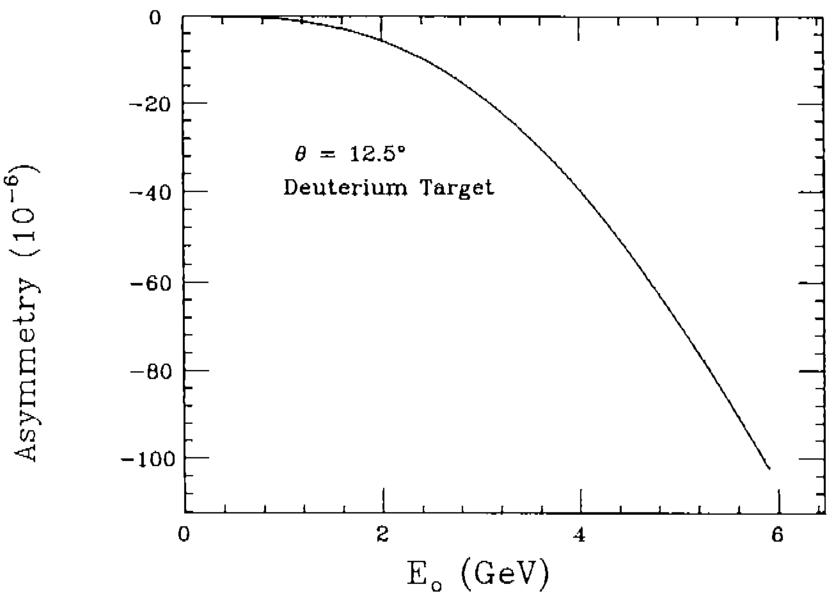

Figure 3c

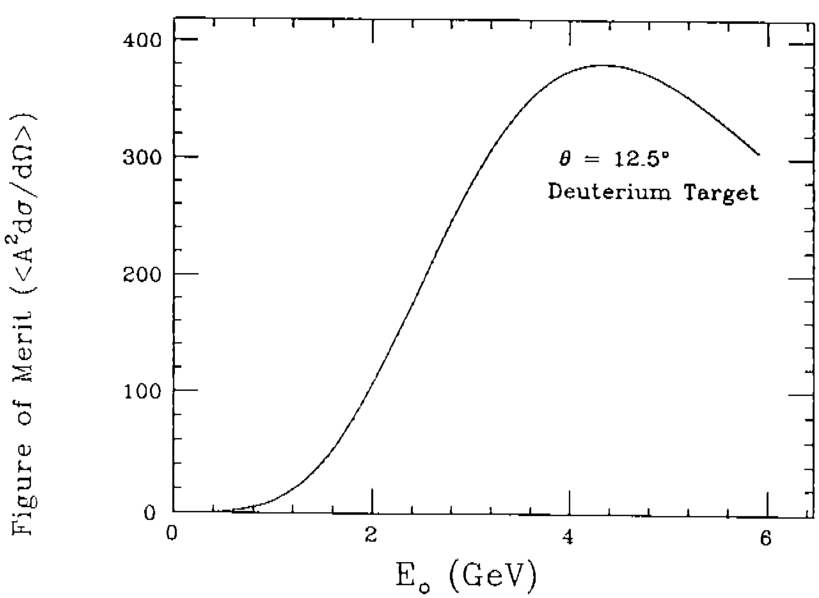

Figure 4a

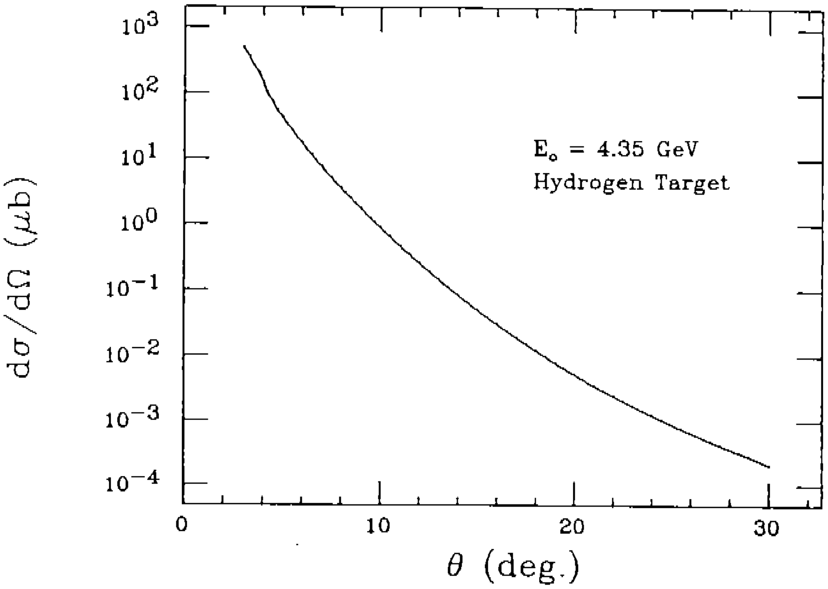

Figure 4b

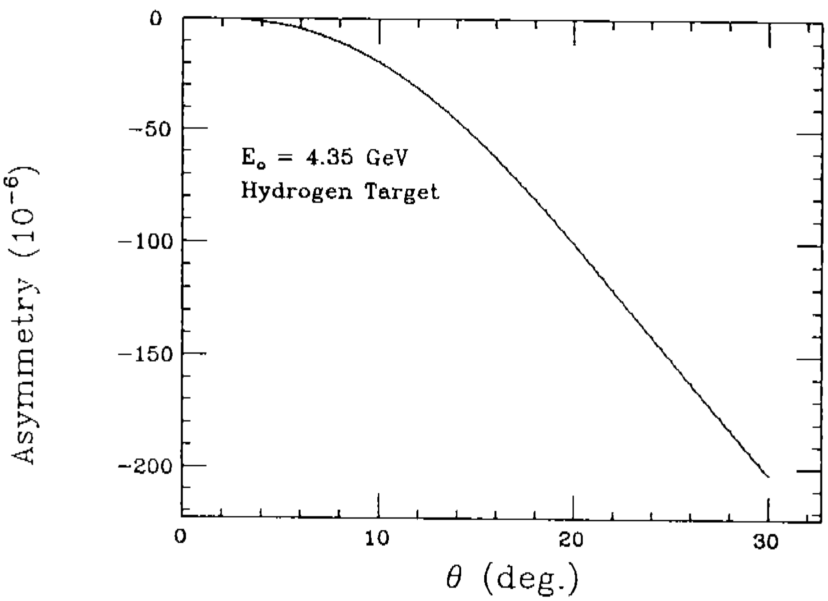

Figure 4c

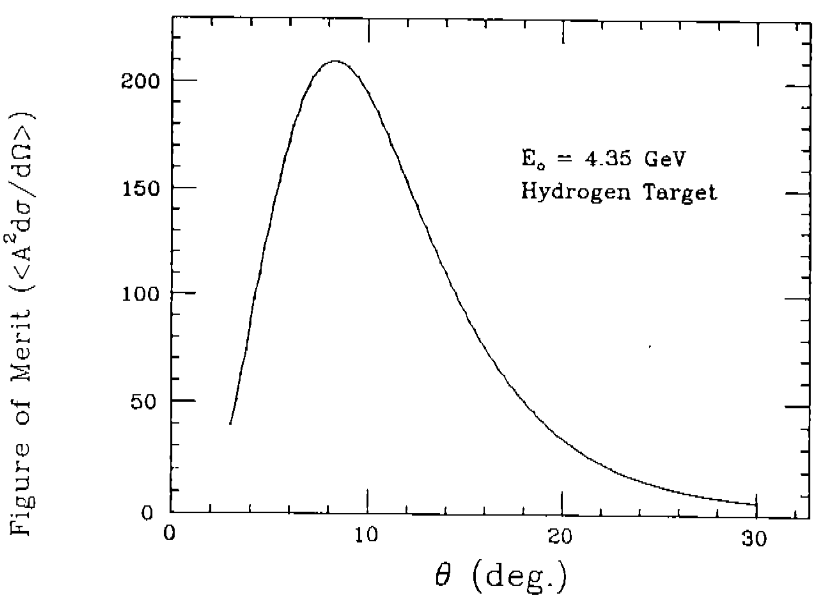

Figure 5a

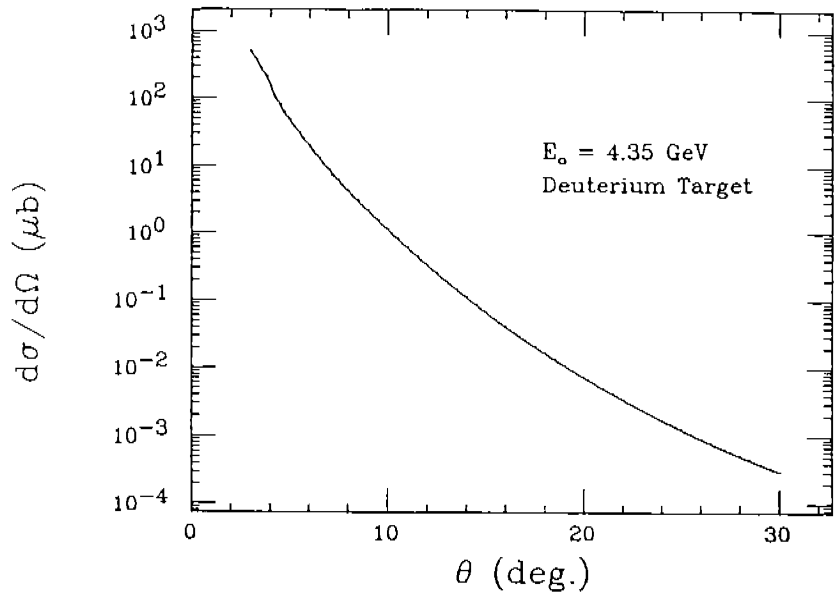

Figure 5b

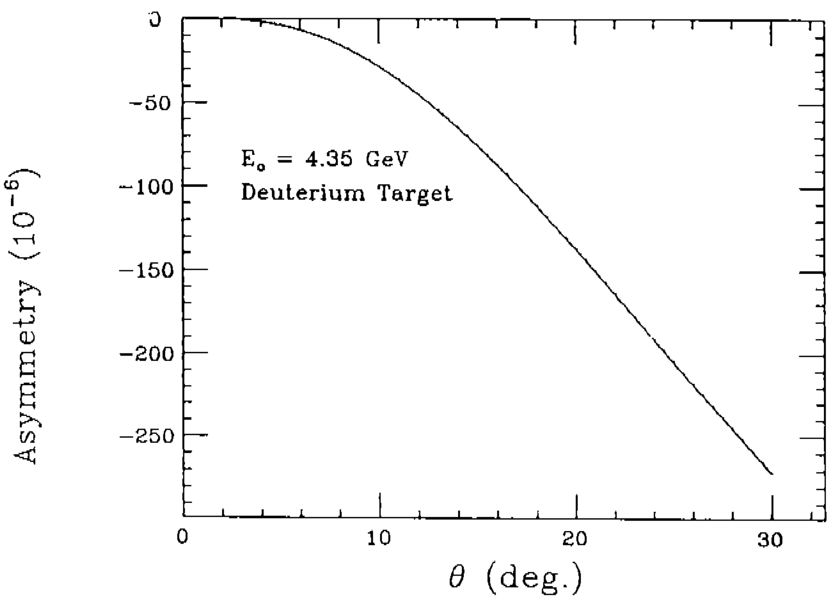

Figure 5c