CEBAF PROPOSAL COVER SHEET

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12000 Jefferson Avenue
Newport News, VA 23606

and received on or before OCTOBER 31, 1989

A. TITLE: STUDY OF MULTI-NUCLEON KNOCKOUT WITH THE CEBAF LARGE ACCEPTANCE SPECTROMETER (CLAS)

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C. THIS PROPOSAL IS BASED ON A PREVIOUSLY SUBMITTED LETTER OF INTENT

/X/ YES
/ / NO

IF YES, TITLE OF PREVIOUSLY SUBMITTED LETTER OF INTENT

LOI # 88-21 MULTI-NUCLEON KNOCKOUT STUDY IN THE LAS
LOI # 88-79 A STUDY OF TWO-BODY CORRELLATIONS IN ^{3}He USING THE (e,e'pp) REACTION

D. ATTACH A SEPARATE PAGE LISTING ALL COLLABORATION MEMBERS AND THEIR INSTITUTIONS

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contact: Miskimen

Study of Multi-Nucleon Knockout with the CEBAF Large Acceptance Spectrometer (CLAS)

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Abstract

We propose to make a survey measurement of multi-nucleon knockout reactions using the CLAS. There are several areas of interest which are covered in the proposal. These include: (1) decomposition of the inclusive cross section into multiparticle final states, (2) three-body currents, (3) meson exchange currents, (4) nucleon-nucleon ground state correlations, and (5) evidence for multiquark clusters (6q, 9q,...). Data will be taken on ^{3}He, ^{12}C, ^{56}Fe, and ^{208}Pb. This survey program can be carried out with the initial complement of equipment proposed for the CLAS and 1200 hours of beam time.

Overview

Two-nucleon knockout and higher multiplicity studies have not been seriously attempted due to the unavailability of high duty factor/high energy electron accelerators and large acceptance spectrometers. Cross sections for two-nucleon knockout are of order pb/(sr-MeV)^3, hence counting rates are low. Experiments with modest solid angle, discrete magnetic spectrometers together with high luminosities have unacceptably high accidental coincidence rates. The CLAS detector at CEBAF will be ideally suited to this type of work, with a solid angle covering a large fraction of 4π sr. Operation at a luminosity of $10^{34} cm^2 s^{-1}$ yields typical count rates for specific multi-nucleon kinematics of 10-100 events/hr with negligible accidentals. Our focus will be on processes in the continuum where the momentum resolution of the CLAS is adequate.

The large acceptance of the CLAS detector plays an important role in the physics program and permits the simultaneous measurement of cross sections over a large kinematic range. For example, at an incident electron beam energy of 2GeV, the acceptance of the CLAS detector allows simultaneous measurements covering $Q^2 = .1 - 1GeV^2/c^2$ and $\nu = .05 - 1GeV$ on a ^3He target (see Figure 1). The acceptance for the electron at small ν can be achieved setting the magnet to bend electrons away from the axis.

For large energy loss ν, nucleons can have substantial opening angles (of order 100° for two nucleon emission), and for hadron multiplicity greater than two, the angular distributions may be nearly isotropic. The acceptance for multi-body final states has been studied using the FAST Monte Carlo. * For the specific case of $e^3He \to e\prime ppn$, we have calculated the acceptance for all four particles in the final state over the allowed phase space for the reaction. The acceptance is uniform over the entire region (see the Dalitz plots in Figures

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* E. S. Smith, "Fast Monte Carlo Program for the CLAS Detector," CLAS-NOTE-89-003,009.

2 and 3.), but varies from 20% to 25% depending on the electron kinematics.

The detection of neutrons is generally required, except in some special kinematic circumstances. The detection of neutrons over the entire solid angle will come from the 5cm thick scintillator layer surrounding the CLAS, with an efficiency of 5%. The shower counters can detect neutrons with an efficiency of 60% and cover 1.5 sr, a substantial coverage. Despite the low efficiency for neutron detection, the np-knockout cross sections are 10-100 times larger than the cross sections for pp, so the yields for the two studies are comparable.

The large acceptance of the CLAS is not only required to obtain acceptable count rates, but the out-of-plane capability also has extremely important consequences for the physics. The LT and TT inteference terms in the cross section depend on $\cos(2\phi)$ and $\cos(\phi)$ respectively. Thus the study of cross sections as a function of the azimuthal angle ϕ about the momentum-transfer vector provides a tool for separately determining those components of the cross section which are of interest while suppressing others which constitute background.

There is no viable alternative to the CLAS for a survey of 4N and higher multiplicity knockout. Even with single particle acceptances as high as 70%, the overall efficiency for detecting multi-partilce final states suffers as multiplicity increases. However, significant sharing of momentum and energy by many nucleons is of significant interest and may be investigated through the study of multi-nucleon events.

The details of this proposal are contained in two contributions which emphasize different aspects of the multi-nucleon study. While the emphasis of the physics varies, the data base for the various investigations is common. We feel that the physics issues of multi-nucleon processes cannot be understood in isolation but as parts of a systematic program.

Summary and Beam Time Request

We are requesting 1200 beam hours to take data with the CLAS detector to make a systematic study of multi-nucleon knockout from ^3He, ^{12}C, ^{56}Fe and ^{208}Pb. About half the beam time will be devoted to the study on ^3He. Our rate estimates are based on 2 GeV incident energies, an energy which should be available for early experiments at CEBAF. The results will set benchmarks for establishing the phenomenology of all multi-nucleon knockout processes.

Nucleus	Beam hours	Beam energy (MeV)	n detection	Nucleon Mult.
^{3}He	500	2000	No	2
^{12}C	170	2000	Yes	2-4
^{12}C	170	1000	Yes	2-4
^{56}Fe	170	2000	Yes	2-4
^{208}Pb	170	2000	Yes	2-4

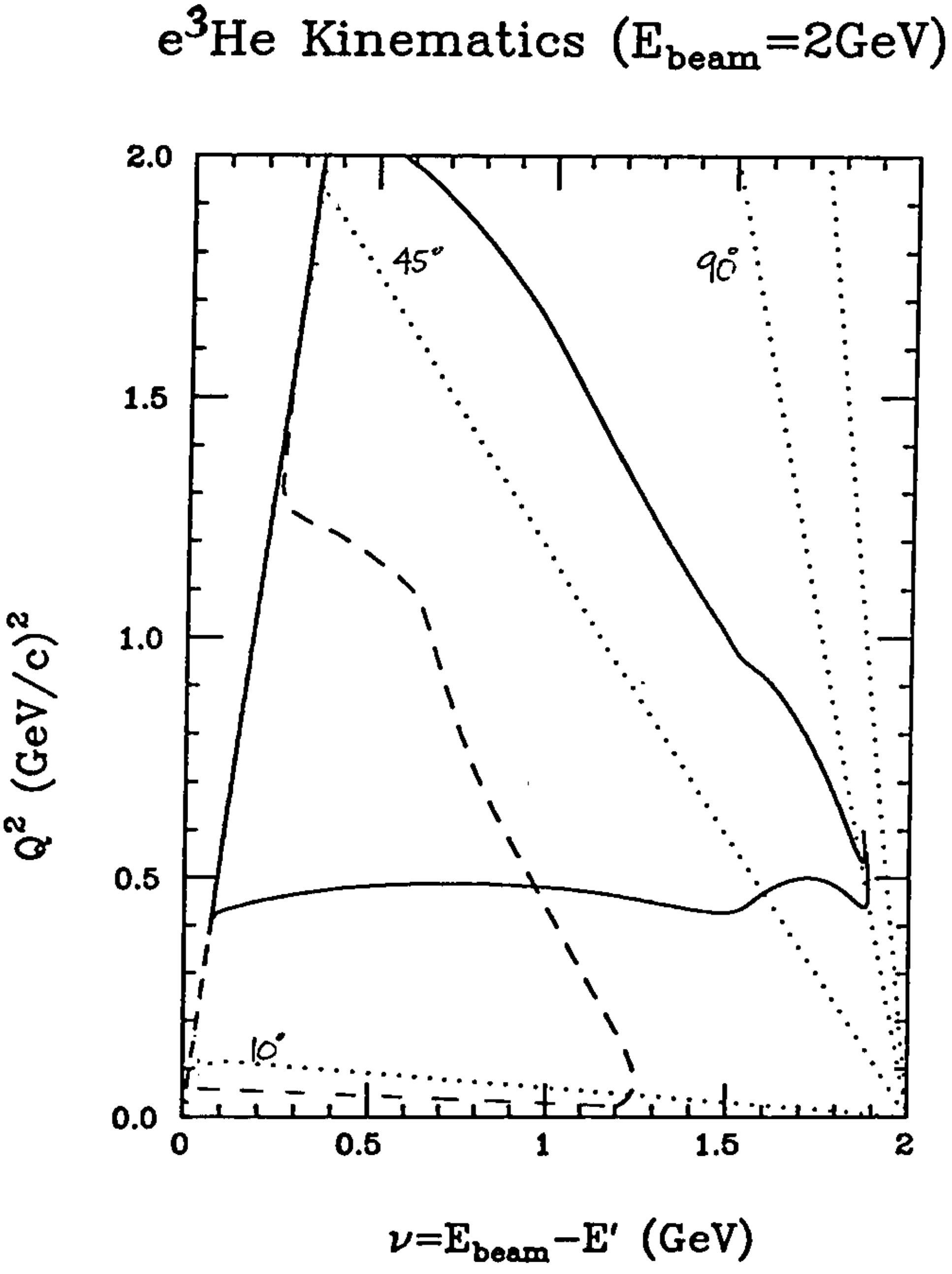

Figure 1: Acceptance for the electron scattering off a ^3He target in the $Q^2 - \nu$ plane. The region inside the solid curve is the acceptance for one magnet polarity. The region inside the dashed curve gives the acceptance for the other polarity. The dotted lines define fixed scattering angles.

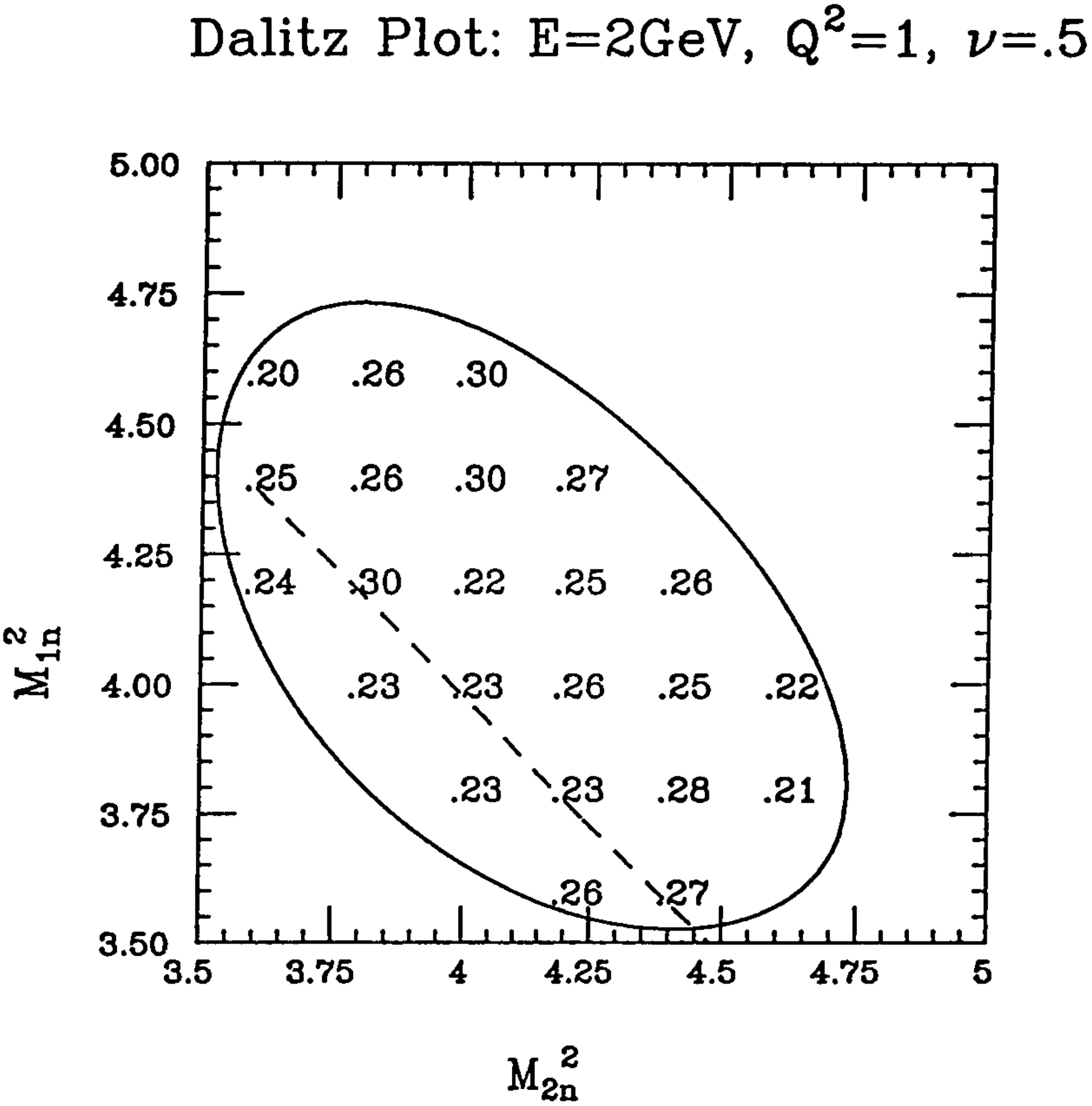

Figure 2: The kinematically allowed region of 3-body phase space for $e^3He \rightarrow e'ppn$. The numbers show the uniform acceptance probability for the four particles in the final state. However, the neutron detection efficiency is not included. The average acceptance at $Q^2 = 1 GeV^2/c^2$ is 25%. The dashed line shows the kinematics for a spectator neutron.

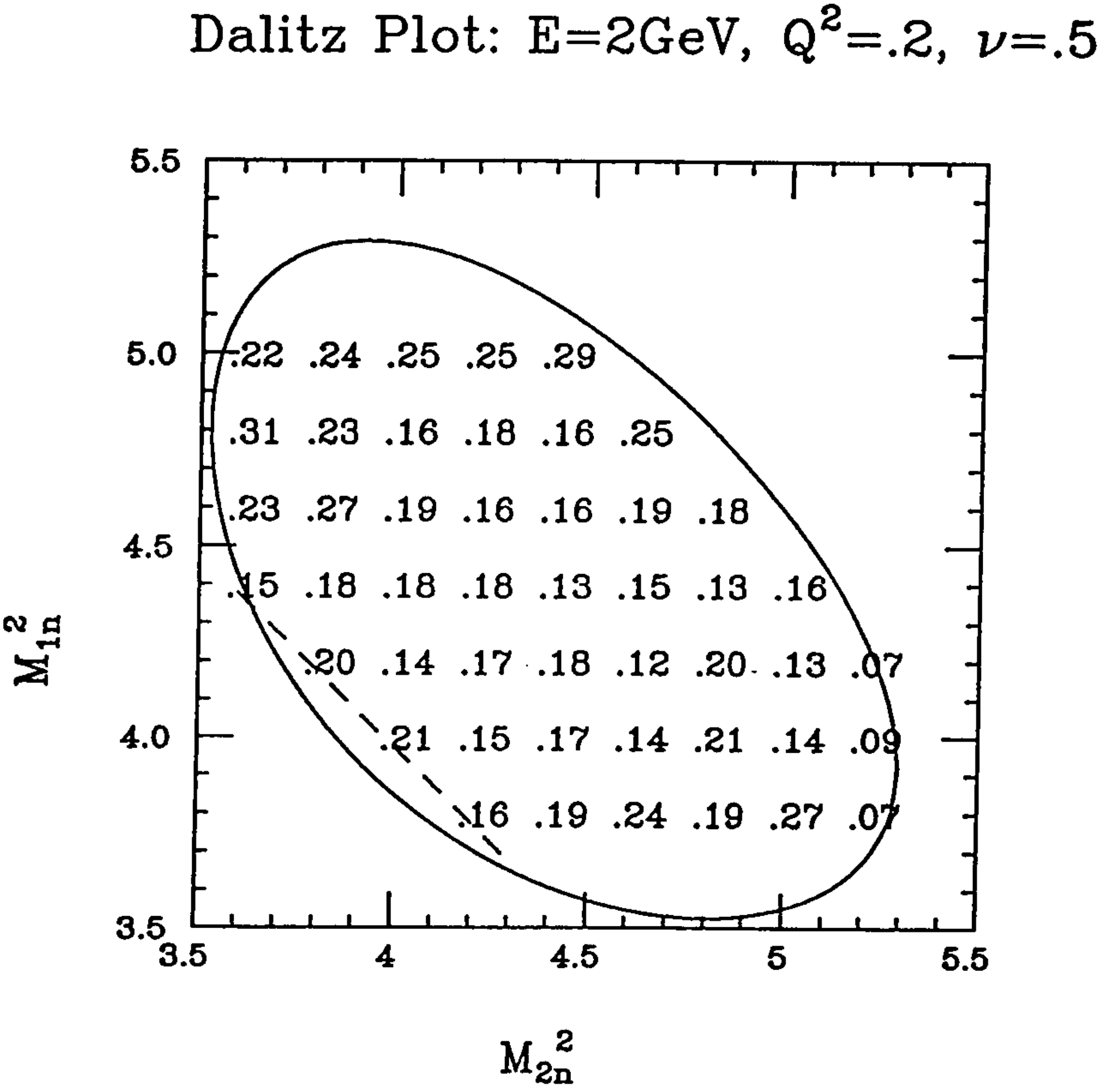

Figure 3: The kinematically allowed region of 3-body phase space for $e^3He \rightarrow e'ppn$. The numbers show the uniform acceptance probability for the four particles in the final state. However, the neutron detection efficiency is not included. The average acceptance at $Q^2 = .2GeV^2/c^2$ is 19%. The dashed line shows the kinematics for a spectator neutron.

Multi-nucleon knockout study using the CLAS

J. W. Lightbody Jr. and R. A. Miskimen

Introduction

The goal of this collaborative proposal is to study the general phenomenology of multi-nucleon emission. Since very little electro-production data exists on this reaction, the proposed experiment can be considered a survey experiment. Nearly everything that can be measured on this reaction with the CLAS will be new information. The most important aspect of the experiment will be to establish the systematics of multi-nucleon emission. For example, (e, e′p) experiments have found evidence for multi-nucleon emission at kinematics away from the quasi-elastic peak. A high priority for this experiment will be to scan the region from the low excitation side of the quasi-elastic peak to above the delta, and determine the probability for one nucleon emission, two nucleon emission, and so forth. Studies should be done as a function of mass number, starting with $A = 3$ and going up to heavy nuclei. Neutron detection is going to be important in these studies, particularly for nucleon multiplicities greater than two. Previous contributions to the CEBAF PAC have discussed survey measurements of this type.

This contribution to the multi-nucleon knockout proposal focuses on four specific topics that can be addressed in a survey measurement. The topics are three-body forces, nucleon-nucleon correlations, delta damping through the four nucleon emission process, and evidence for 6-quarks bags. We believe that ^{3}He is the best nucleus for starting a program of (e, e′pp) studies, and much, but not all, of the work presented here deals with ^{3}He. Similarly, we believe the first round of (e, e′NN) experiments at CEBAF will be (e, e′pp) experiments, as opposed to (e, e′pn) experiments. While the (e, e′pn) reaction is interesting for its own reasons, in this contribution we present detailed count-rate estimates for only the (e, e′pp) reaction. Therefore, the discussion will be limited largely to the (e, e′pp) reaction.

Theoretical overview of the ^{3}He(e, e′pp) reaction

^{3}He is the most fundamental system in which correlation effects can be directly observed. Laget [LA87] has attempted the first (e, e′pp) cross section calculations for ^{3}He, including initial-state correlations (Faddeev calculation of the ground state), meson exchange currents (MEC), and final-state rescattering effects. The transverse cross section is dominated by contributions from MEC effects, including delta production. The longitudinal cross section is dominated by rescattering effects at electron energy losses (ω) below 200 MeV, but at higher ω there is hope of extracting information concerning initial state correlations.

Figure 1 shows Laget's calculation for a 2 GeV beam, a scattering angle of 15°, a proton emission angle in the center of mass of $\theta_{c.m.} = 90°$, and leaving the neutron at rest. The impulse approximation result is purely longitudinal and is shown by the dashed curve. The solid curves show the results for the longitudinal and transverse cross sections when all final-state interactions and meson exchange currents are included. There are three different kinematic regions, each with different physics, that are spanned in Laget's calculation. The first region is at low excitation, where the longitudinal cross section dominates but the final-state interaction (FSI) between the two outgoing protons is very strong. The transverse part of the cross section is suppressed because a correlated pp pair in a T=1 $^1S_0$ state has no dipole moment with which the photon can interact. The final-state interaction between the protons is strong because the center of mass kinetic energy of the correlated protons is low. The second region is from 200 MeV to 300 MeV, where the longitudinal cross section still dominates and the FSI is not strong. It is in this region that one might hope to study two-nucleon correlations. Finally, the third region is at 300 MeV and beyond, where the transverse cross section dominates because of delta-resonance excitation.

In order to study these processes, we must be able to separate the longitudinal and transverse cross sections. The following expression is the general (e,e'pp) cross section when the two-nucleon system cm moves along the momentum-transfer direction:

$$\frac{d^5\sigma}{d\Omega_e dE_e dp_1 d\Omega_1 d\Omega_2} = \Gamma_v \frac{p_1^2 p_2}{E_1} \left(\frac{Q}{p}\right)_{c.m.} \times$$

$$\left[\sigma^T + \epsilon\sigma^L + \epsilon\cos(2\phi)\sigma^{TT} + \sqrt{\frac{q_\mu^2 \epsilon(\epsilon+1)}{2\omega^2}}\cos(\phi)\sigma^{LT}\right]$$

where Γ_v is the virtual photon flux, and $(p, Q)_{c.m.}$ are the proton relative-momentum and total energy in the pair cm system. More complicated forms result when the 2N pair does not move along q. In Laget's work, the transverse-transverse interference term (TT) is essentially the same as the direct transverse cross section term (T), while the LT interference term is negligible. As a result, one can suppress transverse cross sections by proper choice of the virtual photon polarization (ϵ) and "out-of-plane" angle (ϕ). Because of the small cross sections, it will be impractical to perform conventional Rosenbluth separations; hence, the ability to suppress the transverse strength compared to longitudinal strength may be our best hope of isolating the two. Out-of-plane capability provided for naturally in the CLAS is therefore extremely important.

We have made a rate calculation to demonstrate the feasibility of the proposed study. Figure 2 shows results based on Laget's work for 2 GeV electrons scattered at 15^o, with the two outgoing protons sharing the momentum-transfer symmetrically. A luminosity of $10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ has been assumed. The upper portion of Figure 2 shows the inclusive result. It is obvious from the huge number of events that the trigger system will have to prescale the enormous flux of quasi-free or near-quasi-free events. The lower portion of Figure 2 is relevant to the present study and simulates results from a 500-hour run. The electron spectrometer acceptance was 100 msr/20 MeV, with an efficiency (resulting from finite coil extent) of 60 percent. The proton arm was developed by revolving a 200 mr cut in the angle θ_{pq} about the q-direction. The assumed energy acceptance was 20 MeV. An average Figure of 70 percent was used for the proton detection efficiency, again resulting from finite coil extent.

As Figure 2 shows, the $\cos(2\phi)$ dependence is striking in the simulated data, particularly at excitation energies near the delta where the transverse component is strong. A $\cos(\phi)$ component is not present in the simulated data because in Laget's calculation the σ^{LT} term is small. We conclude that by studying the cross section as a function of the out-of-plane angle, it will be possible to estimate the transverse strength in the cross section. Given a theoretical model relating σ^{TT} to σ^{T}, it might be possible to isolate the transverse cross section.

Study of three-body forces using the ^{3}He(e, e$'$pp) reaction

We propose to measure cross sections corresponding to approximately equal sharing of the momentum-transfer between all three nucleons. For example, this process might proceed through electro-pion production on a single nucleon, followed by pion absorption on the remaining pair. There is now evidence from Glöckle *et al.* [GL88] that purely binary potential models for the three-body system fail to describe the n + d → n + n + p cross section and analyzing power at low energies. These results, together with the possible need for three-body forces (3BF) in binding energy calculations, suggest that it is interesting to explore other manifestations and/or structures of 3BF at higher energies and momentum-transfers. The goal of this study is to isolate three-body processes and to study the momentum and energy-transfer dependence of the reaction. For simplicity, we propose to study only those final-states without pions by so restricting the spectator-missing-mass.

There are two configurations of outgoing nucleons that appear to be most sensitive to three-body effects, according to Glöckle; these are the "star" and "co-linear" geometries. The star configuration arises in the symmetric c.m. breakup, 120^o between nucleon; whereas the co-linear configuration arises when one of the nucleons is at rest in the c.m. system. In both cases the nucleons move perpendicular to the momentum transfer direction in their c.m. system. Calculations in progress by Laget [LA89] indicate that the star geometry minimizes nucleon-nucleon rescattering. There are, howver, other important variations to consider with respect to 3BF. If kinematics are chosen to enhance the importance of processes such as quasi-free pion production followed by absorption on the remaining pair, then, as Treiman and Yang have shown, the cross section should be rotationally invariant about the pion propagation direction. Use of the CLAS permits such cuts to be examined in detail easily, and should provide indication when the corresponding amplitude is dominant.

We have investigated the acceptance of the CLAS for three types of three-nucleon emission geometries: (a) the star geometry, (b) the co-linear geometry, and (c) a geometry where $P_1 = P_2 = P_n$ but the angular distribution is isotropic in the c.m. The calculation was done for ^{3}He and a fixed c.m. kinetic energy of 300 MeV. The acceptance was calculated using the FASTMC simulation code [SM89], reducing the CLAS magnetic field to 50 percent of its nominal value to improve acceptance at low momentum-transfer. Figure 3 shows the results of the acceptance calculations for all three geometries as a function of momentum-transfer at fixed $T_{c.m.} = 300\text{MeV}$. The acceptances for all three geometries are approximately equal, and increase from about 20 percent at $Q^2 = .2\text{GeV}^2/c^2$ to about 40 percent at $Q^2 = 1.62\text{GeV}^2/c^2$. Figure 4 shows the missing mass distribution for the emission geometry with isotropic angular distribution in the c.m. and $P_1 = P_2 = P_n$. The FWHM of the missing mass distribution is 20 MeV, which is more than adequate to reject final states with pions. The missing mass distribution shown in Figure 4 is actually broader than the usual representation of the CLAS missing mass resolution because the magnetic field was reduced to 50 percent of its nominal value in this example.

Pion absorption experiments have shown dramatic evidence for a three-body absorption process. Figure 5 shows a proton angular distribution from the ^{3}He(π^+,pp) experiment of Backenstoss *et al.* [BA85]. The two-nucleon absorption peak sits on top of a broad distribution that is approximately two orders of magnitude below the peak value (note that the scale in Figure 5 is logarithmic). A Monte Carlo simulation of the 3N decay, assuming a constant matrix element, agrees very well with the shape of the broad component in the angular distribution. Assuming a pure phase-space behavior for the three-body absorption, Backenstoss *et al.* integrated the broad component in the angular distribution and obtained a total cross section of 3.9 ± 0.5 mb.

We will now use the ^{3}He(π^+,pp) data to make count rate estimates for ^{3}He(e,e'pp) three-body absorption. At excitation energies near the delta it has been demonstrated that the (γ,p) and (π,p) reactions are closely related; the ratio of photon to pion cross sections is approximately constant and equal to $\frac{1}{55}$ [MC80b][SC83][AS86]. To make count-rate estimates for the (e,e'pp) reaction, we will assume that a similar relationship holds between three-body photodisintegration and three-body pion absorption cross sections. Figure 6 shows the Feynman diagrams for the (π,NN) and and (γ,NN) processes, and illustrates the similarities between the processes. The diagrams shown in Figure 6 are expected to be the dominate processes at excitation energies near the delta, which is where we will present count-rate estimates. To make count-rate estimates for three-body electro-absorption we will make the following approximation:

$$\frac{d^2\sigma_{3N}}{d\Omega_e d\omega_e} = \sigma(\pi,3N)\frac{\sigma(\gamma,p)}{\sigma(\pi,p)}\frac{\sigma_{Mott}(\frac{1}{2}+\tan^2\frac{\theta_e}{2})F_\Delta^2(Q^2)}{\sigma_T}$$

$\frac{d^2\sigma_{3N}}{d\Omega_e d\omega_e}$ = three-body electro-absorption cross section for (e,e')

$\sigma(\pi,3N)$ = pion three-body absorption cross section

$\frac{\sigma(\gamma,p)}{\sigma(\pi,p)} = \frac{1}{55}$, the ratio of photon-proton to pion-proton emission cross sections

σ_{Mott} = Mott cross section

σ_T = total photo-absorption cross section at the delta

$F_\Delta^2(Q^2)$ = delta form factor.

If all of the three-body phase space could be observed then the (e,e'pp) count-rate would be high and of the order of hundreds of events per hour. In practice the CLAS has an acceptance of about 30 percent for the three geometries we have considered. Furthermore, the phase space in these geometries is only a small fraction of the total three-body phase space. Consider the isotropic emission geometry where $P_1 = P_2 = P_n$, and assume a momentum acceptance of 10% for all three hadrons. Then a conservative estimate of the percentage of total phase space covered in this geometery would be $(\Delta p/p)^3 = .1$ percent. At present we are working on a more detailed calculation of the phase space covered in each of the three geometries using a Monte Carlo technique. Figure 7 shows the estimated cross section as a function of Q^2 at a fixed center of mass kinetic energy, $T_{c.m.} = 300$ MeV. Count-rate estimates were made using the isotropic emission geometry, bin widths $\Delta Q^2 = .1 \mathrm{Gev}^2/c^2$ and $\Delta T_{c.m.} = 50$ MeV, and a phase space coverage of .1%. The error bars on the figure show the anticipated statistical error in a 500-hour experiment. Although the kinematics demonstrated in Figure 7 are at the peak of the delta, it is just as important to to study the energy transfer behavior of the cross section because the reaction mechanism should be quite sensitive to energy transfer. Using the CLAS it is straightforward to do this because all of the data can be taken simultaneously.

It is important to be able to distinguish between two-step reactions and a genuine three-nucleon mechanism. For example, in a two-step reaction a nucleon can create a pion through the (γ, π) reaction, which is then absorbed in a two-nucleon absorption process. In this process the mass of the intermediate pion would be close to its mass shell. The particle labeled "x" in Figure 6 would be the intermediate pion in this example. For a three-body reaction, however, the "x" particle would not necessarily be a pion and it would not be on the mass shell. Therefore, the mass of x, M_x, should be sensitive to the reaction mechanism. The quantity M_x^2 is given by:

$$M_x^2 = (q + p - p')_\mu^2,$$

where q, p, and p' are the four-momenta of the photon, the nucleon before photon absorption, and the nucleon after pion emission. In actuality, the initial four-momentum of the nucleon is not known because of Fermi motion in the nucleus. To further complicate matters, any of the three nucleons could have absorbed the photon, which leads to an ambiguity in the value of M_x^2, there being three possible values for M_x^2. It has been shown that these ambiguities do not substantially lessen the sensitivity of this parameter to the reaction mechanism if the following approximations are made [BA89]; calculate M_x^2 assuming the nucleon is initially at rest, and use the value of M_x^2 closest to the pion mass. To illustrate this technique, Figure 8 is a plot of the M_x^2 distribution for the isotropic emission geometry ($P_1 = P_2 = P_n$). Note the smooth distribution in M_x, reflecting the three-body phase space, and the absence of any peak near $M_x^2 = M_\pi^2$. A Fermi motion smeared peak at that location would be a signal for a two-step reaction. When studying three-body reactions with the CLAS, it will be possible to place cuts on M_x^2, thereby limiting two-step reactions.

Study of two-nucleon correlations in ^{3}He using the (e,e′pp) reaction

Numerous experiments have claimed evidence for two-nucleon correlations. These measurements include (e,e′p) experiments, (γ,pn) and (γ,pp) experiments, pion double charge-exchange experiments, pion absorption experiments, and a measurement of the Coulomb sum rule in ^{3}He. The last example, the Coulomb sum rule, is perhaps the best evidence we have of the presence of two-proton correlations [SC89]. However, we conclude that the evidence, while persuasive, does not provide answers to all of our questions. In particular, the present experiments do not probe two-nucleon correlations as a function of momentum and energy transfer in kinematics where final-state interaction and delta excitation are minimized. The (e,e′pp) reaction, however, can be used to study two-nucleon correlations. Under certain very restricted conditions the (e,e′pp) cross section is proportional to the square of the pp relative wave function. In this approximation the wave function is a function of the relative momentum between the two correlated nucleons before absorption of the virtual photon. This is usually demonstrated by using the impulse approximation in conjunction with the following assumptions; assume plane waves for the protons, consider only the longitudinal cross section, take the correlated protons at rest initially, and consider only symmetric emission ($\theta_{c.m.} = 90°$). Taking the correlated nucleons to be at rest initially is not a serious restriction because $P_n = 0$ actually maximizes the cross section; the neutron is in an s-state relative to the correlated pair. Figure 9, which shows the IA diagrams for the (e,e'pp) reaction, illustrates why it is necessary to consider symmetric emission. As shown in the figure, the virtual photon can be absorbed on either proton, which leads to an ambiguity in the relative momentum that is being measured in the reaction. In this case

$$\vec{P}_{rel} = \frac{1}{2}(\vec{P}_1 - \vec{P}_2 - \vec{q})$$

or

$$\vec{P}_{rel} = \frac{1}{2}(\vec{P}_1 - \vec{P}_2 + \vec{q})$$

To eliminate this ambiguity we will take $\vec{P}_1 - \vec{P}_2$ perpendicular to $\vec{q}$, which is equivalent to $\theta_{c.m.} = 90°$. Under these conditions it can be shown that $P_{rel} = P_1 = P_2$, where P_1 and P_2 are the laboratory momenta for the two emitted protons.

The approximations that have been used neglect several important effects: distorted waves, final-state interactions and meson exchange currents, and transverse excitation, in particular the presence of the delta. These problems cannot be eliminated but they can be minimized in a ^{3}He(e,e'pp) experiment. Note that in the (e,e'pp) reaction there are no charged meson exchange currents between the protons, and neutral pions do not couple to the photon. Delta excitation is suppressed because the dominant spin-parity of the $p\Delta^+$ state is $J^\pi = 1^+$; hence the $p\Delta^+$ cannot decay back into the pp channel. Final-state interactions cannot be eliminated, but they can be minimized and held constant by fixing the kinetic energy in the center of mass of the pp system in a range between 100 MeV and 150 MeV. Because the counting rates are low, Rosenbluth separations will not be feasible. However, the experiment can be done at forward electron-scattering angles with high beam energies to make the longitudinal photon polarization, ϵ_L, greater than one and minimize the importance of the transverse cross section. By going "out of plane" it will be possible, if the count-rate is large enough, to measure the σ^{TT} term in the (e,e'pp) cross section, and from this to gauge the transverse strength. Also, nuclear excitation energies can be kept below the delta peak to suppress delta excitation.

For several reasons we believe ^{3}He is an ideal nucleus to initiate a program at CEBAF of two-nucleon correlation studies using the (e,e'pp) reaction. On the theoretical side, three-body wave functions can be calculated accurately using the Fadeev equations. ^{3}He wave functions that contain all the bound state two-body correlations are currently available, and three-body scattering wave functions containing all final-state interactions should be available within the next few years. Also, meson exchange current mechanisms can be estimated reasonably well. On the experimental side, the mass number dependence of electron and proton singles rates and true rates indicate that trues to accidentals are probably optimized for light systems. In addition, background studies that were initiated to estimate the maximum usable luminosity in the LAS, indicate that the luminosity is maximized for a light nuclear target. The maximum usable luminosity in the LAS will probably be at least $L = 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$.

The kinematics that we have chosen are intended to limit the importance of FSI and the transverse cross section. To minimize and hold the pp FSI constant, the pp center of mass energy, $T_{c.m.}$, was fixed at 150 MeV. This energy corresponds to the minimum in the proton-proton scattering cross section. Using a theoretical code from Laget, $^3He(e,e'pp)$ cross sections were calculated in PWBA and used to make count-rate estimates.

Count-rates were estimated assuming $E_i = 2000$ MeV and $L = 10^{34} cm^{-2} s^{-1}$. The data were sorted into bins of width $\Delta P_{rel} = 50 MeV/c$, $\Delta q = 50 MeV/c$ and $P_n < 100 MeV/c$, and count-rates were estimated as a function of P_{rel}. Count-rate estimates were made by rotating the proton vectors around $\vec{q}$ and integrating the cross section, and then by rotating the scattered electron vector around the beam axis and integrating the cross section. The solid angle and momentum phase space corresponding to the established bin widths in q P_{rel} and P_n was calculated with a Monte Carlo technique. The CLAS acceptance was calculated using the FASTMC simulation. To maximize acceptance at low and high P_{rel}, the CLAS magnetic field was reduced in the simulation to 50 percent of its nominal value. The calculated acceptance for these kinematics as a function of P_{rel} is shown in Figure 10. The figure shows that the typical CLAS acceptance for this type of event is approximately 30 percent. The missing mass resolution is similar to the distribution shown in Figure 4, with a FWHM of 20 MeV.

A single event display of a typical quasi-deuteron-like $^3He(e,e'pp)$ event in the CLAS is shown in Figure 11. In this event the two protons carry off most the energy and momentum from the virtual photon, and the neutron recoils with the fermi momentum it possessed inside of the nucleus. Figure 12 is a picture of the same event, but viewed from along the axis direction. Figure 13 shows the theoretical cross sections as a function of the relative momentum between the correlated protons. Also shown are the statistical errors that would be anticipated in a 500-hour experiment with a luminosity of $L = 10^{34} cm^{-2} s^{-1}$. Note that despite the small cross sections, a significant measurement can be made for relative momenta all the way up to 700 MeV/c. The count-rates and kinematics for the experiment are given in Table 1.

Accidental backgrounds were estimated by calculating the accidental coincidence rates $(e,e'p) \times (e,p)$ and $(e,e') \times (e,p) \times (e,p)$. The (e,e') singles rates were estimated using y-scaling [BO82], and the (e,p) singles rates were estimated using the EP code of O'Connell and Lightbody. The $(e,e'p)$ coincidence cross section was estimated using standard techniques [KL83]. The coincidence timing resolution was assumed to be 2 nanoseconds. For all values of P_{rel} considered, the accidentals rate is always much less than the trues rate, and even in the worse case the trues to accidentals ratio is 5 to 1. Also, for all P_{rel} considered the three-fold coincidence $(e,e') \times (e,p) \times (e,p)$ dominated the accidental rates. The anticipated trues-to-accidental ratios are also given in Table 1.

Four-nucleon knockout from nuclei with A$\geq$ 4

For A$\geq$ 4 we can also ask if there is any evidence for significant sharing of momentum and energy between four nucleons, as suggested by Brown [BR82] in the case of pion absorption through a "double-delta" mechanism. The evidence behind this speculation came from (π,p) data of McKeown *et al.* [MC80a]. Their rapidity analysis revealed that approximately four nucleons were involved in the pion absorption process. We propose to explore the excitation energy dependence of this process, as well as its q-dependence and A-dependence. The LAMPF pion data were taken at the peak of the Δ-resonance. According to Brown, the sharing of energy following double-delta production moves the deltas well below the resonance peak, and the reduced strength of the $\Delta - \Delta$ compared to the N-Δ transition potential leads to 4N final states with no further Δ-production. We will look at higher excitation energies, where more than two Δs may be produced, leading possibly to higher-multiplicity final states. There are no viable alternatives to the CLAS for such survey work. Even with an acceptance near 4π, at each increase in multiplicity by an additional particle we face an additional 70 percent efficiency factor (0.70*.05 for neutrons). We should be able to measure up to 4N knockout and infer the fraction of higher multiplicity events.

In order to estimate rates for the double-delta process, we assume that 10 percent of the inclusive cross section in the Δ-region goes via 4N knockout. We again consider a 2 GeV beam energy, scattering at 15°, and an energy loss of 400 MeV. We consider that the emission should be isotropic. We will be detecting neutrons as well as protons in this example. The solid angles are as discussed previously. In addition, we estimate the losses in proton detection efficiency due to the roughly 150 MeV/c low momentum cutoff of the LAS at an overall 20 percent. We estimate the $(e,e'4N)$ rate at a respectable 13 counts/hour, assuming a luminosity of 10^{34} cm^{-2}s^{-1}. The 3m TOF should provide 8 percent energy resolution for 100 MeV neutrons. Based on this rate, we propose to devote 125 hours of running to this measurement. As will be discussed below, the same amount of time would be devoted to each of three other targets: A=12, 60, and 208; and in a total of 500-hours we could have a reasonable picture of this 4N, and of course 2N and 3N, absorption process, with data taken simultaneously for many other energy losses and q's.

Σ Knockout of quark clusters

The nuclear density of ^{4}He is substantially greater than the density of ^{3}He; therefore, it is reasonable to look for possible medium effects in the two-nucleon knockout process. The three- and four-body rates in the A=12, 60, and 208 targets should be at least as great as the above estimates, which were clearly great enough to be interesting. However, there are other reasons, that go beyond the conventional nuclear force issues. Are there clusters in the ground state corresponding to six-quark bags? Vary [VA86] has suggested these configurations can be on the 10 percent level; Mulders [MU86] has suggested a higher percentage. He suggests that dibaryons play a role in the quasifree, dip, and delta regions. We need to probe various systems by looking for correlated pairs of nucleons (both pp and pn pairs) coming out with energies and momentum corresponding to Bjorken $X \geq 1$, including near X=2. This is the same excitation region probed by inclusive electron scattering y-scaling studies. The work of Sick, Day, and McCarthy [SI80], in connection with y-scaling, demonstrated the failure of Faddeev calculations to reproduce the observed high-momentum components in the ground state, large negative y. In the absence of theoretical understanding, we propose that (e,e'2N) measurements should be made that span the energy loss region from X=2-3, to well above the Δ-resonance. The CLAS is ideally suited to such studies. In the case of zero recoil momentum, our primary interest, the opening angle for the two nucleons would vary from 0° to 100° (for the case of 2 GeV electrons scattered at 15°). If discrete spectrometers are used, there is a serious mechanical overlap problem.

We estimate count rates for composite 2N knockout based on inclusive data from SLAC (^{4}He) [DA86] and extend this to ^{12}C based on Mulders' estimates of relative single-nucleon and two-nucleon content. We have used the SLAC ^{4}He results for a 2 GeV beam and 15° scattering angle to estimate how large a peak corresponding to 6Q knockout can be supported by the data. The result is that the ratio of 6Q to 3Q cross sections is less than 5 percent for an energy loss of 100 MeV. We assume that the breakup of the 6Q system is isotropic in its cm system, with decay into a neutron and proton. The electron acceptance was as above, 100 msr/20 MeV; the hadronic acceptance was obtained by revolving a 50 mr angular cut about the q-direction, which results in 8 percent of 4π. The global electron and hadron acceptance from finite coil acceptance was as assumed earlier. With a luminosity of 10^{34} cm^{-2}s^{-1}, we obtain a rate of 42 counts/hr. The hadron opening angle for this example is 66°. We did a similar estimate for ^{12}C in the Δ-resonance region, 400 MeV energy loss, and assumed the ratio of 6Q to 3Q cross sections was as given by Mulders (25 percent). For this case we found a rate of 238 counts/hour at an opening angle of 123°. Both of these rates are quite acceptable; and within the 125 hour time proposed earlier for each of the targets A=4, 12, 60, and 208 we would have an excellent survey picture of the 2N knockout process.

Required experimental conditions

The experimental equipment required for this measurement is discussed in detail in the CLAS conceptual design report. We urge that all six segments of the CLAS must be fully instrumented, with drift chambers and time-of-flight counters as part of the initial complement of the detector. In addition, it is essential to have Cherenkov counter and shower counter coverage out to approximately 45° for electron ID. This experiment requires high luminosity running ($L=10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$) on a ^{3}He gas target. Because the electron and proton singles rates will be large, the CLAS will be triggered (possibly at the hardware level) on electron-proton-proton events. Possibly the trigger can be broadened to include electron-proton-pion events, or events with three or more hadrons in the final-state, without a significant rise in deadtime. If count-rate estimates show this to be the case, then this experiment could become part of a general survey measurement. The proton momenta in this experiment range from approximately 400 MeV/c to 700 MeV/c. For proton momenta in this range, no special measures must be taken for particle ID or acceptance. Particle ID will be accomplished through a combination of time-of-flight, dE/dx in the drift chambers and scintillators, and a measurement of the particle momentum.

UMass involvement

The UMass group was very active in the electromagnetic background studies that were made during two runs at the University of Illinois microtron in spring 1988. Since then we have been working with the CLAS drift chamber group. We have agreed to take on two projects related to the drift chambers. One project is to set up a drift chamber in a high magnetic field (2 T) and study how the drift chamber behaves. The goal is to learn how magnetic fields both parallel and perpendicular to the signal wire influence the drift cell. We will be able to test software algorithms for correcting B-field distorted drift spectra, and get a measure of the cell resolution that can be obtained. Bates Linac has agreed to supply the magnet, power, and cooling for the study, as well as a place to work. We are now searching for a uv laser that can be used for the studies.

The other project we have agreed to work on is the drift chamber electronics. CEBAF has a prototype amplifier that is far along in its development stage and will be farmed out to industry. The front-end electronics, which includes the ADC's and TDC's, is not as well developed and requires personnel with experience in fast-analog electronics. UMass probably cannot contribute to the development of the front-end electronics. Our group is willing to handle the supervision of the electronics project, the testing of the components at UMass, and the installation of the electronics on the CLAS. We plan to take an active role in the design of low-voltage and high-voltage power supplies and control circuits. We recently hired a postdoc who will have this project as one of his principle responsibilities. A memorandum of understanding between CEBAF and UMass that details these issues is being written and will be submitted to CEBAF soon.

National Institute of Standards and Technology involvement

We have already developed codes for estimating singles rates for electrons, protons, neutrons, and pions. These codes have been the basis of calculations of accidental coincidences. They will be used in more extensive modeling calculations of the CLAS performance. We have attempted to interface with the lab in a theoretical effort to understand luminosity limitations, based on the relative importance of single-step, wide-angle bremsstrahlung versus two-step electromagnetic effects. We intend to continue a strong involvement with the CEBAF CLAS working group.

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Figure Captions

1. Laget's calculation for the ^{3}He(e,e′pp) reaction [LA87].
2. Count-rate estimates based on Laget's calulation.
3. CLAS acceptance for three-body emission geometries; the solid curve is for isotropic emission in the center of mass with $P_1 = P_2 = P_n$, the dashed curve is the "star" geometry, and the dotted curve is the "co-linear" geometry. The center of mass kinetic energy is 300 MeV.
4. Missing mass distribution for isotropic emission, $T_{c.m.} = 300$ MeV, and $Q^2 = 1\text{GeV}^2/c^2$.
5. Proton angular distribution from the ^{3}He(π^+,pp) reaction [BA85].
6. Feynmann diagrams for the (π,NNN) and (γ,NNN) reactions.
7. Estimated cross sections for the three-body breakup of ^{3}He, in the isotropic geometry. The center of mass kinetic energy is 300 MeV. The errors that are shown are the anticipated statistical errors resulting from a 500-hour experiment.
8. Mass squared of the intermediate boson labeled "x" in figure 6. The Monte Carlo is for the same conditions as in figure 4.
9. PWBA diagrams for the (e,e′pp) reaction.
10. Acceptance as function of relative momentum.
11. Single event display of a quasi-deuteron ^{3}He(e,e′pp) event.
12. Same event as in figure 11, but viewed along the beam axis.
13. Laget's PWBA calculation for ^{3}He(e,e′pp) plotted as a function of the nucleon-nucleon relative momentum. The errors shown are the anticipated errors resulting from a 500-hour experiment.

P_{rel}	E_f	θ_e	ϵ_L	x	θ_{p-max}	θ_{p-min}	$d^5\sigma$	Rate	T/A
450.	1774.	-12.7	1.50	0.41	113.7	00.0	1.3E-7	1.1	200
500.	1729.	-18.1	1.55	0.67	106.4	6.5	3.6E-8	.92	31
550.	1680.	-22.7	1.53	0.87	99.4	11.2	1.1E-8	.30	5.3
600.	1628.	-27.1	1.47	1.03	93.1	13.8	3.3E-9	.085	140
650.	1572.	-31.4	1.40	1.15	87.3	15.2	9.5E-10	.022	55
700.	1514.	-35.7	1.33	1.25	82.1	15.8	3.7E-10	.0089	-
750.	1453.	-40.1	1.24	1.33	77.2	15.8	1.4E-10	.00031	-

Table 1. ^{3}He(e,e'pp) kinematics for $E_i = 2000$ MeV, $T_{c.m.} = 150$ MeV and $\theta_{p-c.m.} = 90°$. P_{rel} is the relative pp momentum, E_f is the final electron energy, θ_e is the electron scattering angle in degrees, ϵ_L is the photon longitudinal polarization, x is the Bjorken variable, θ_{p-max} and θ_{p-min} are the maximum and minimum proton emission angles in degrees, and $d^5\sigma$ is the PWBA cross section $d^5\sigma/d\Omega_e dE_f dp_1 d\Omega_1 d\Omega_2$ in units of $\mu b/MeV^2 sr^3$. Rate is the trues rate in counts/hour assuming $L = 10^{34}$, and bin widths of $\Delta P_{rel} = \Delta q = \Delta P_n = 50$ MeV/c . T/A is the estimated trues to accidentals ratio.

Laget Calculation:

$$\frac{d\sigma}{d\Omega_e\, dp_e\, d\Omega_{p_1}\, dp_{p_2}\, d\Omega_{p_2}} = \Gamma_\gamma \left[\frac{p_1^2 p_2}{E_1} \left(\frac{Q}{P}\right)_{cm} \right] \cdot$$

$$\left\{ \sigma^T + \epsilon\sigma^L + \epsilon\cos 2\phi\, \sigma^{TT} + \sqrt{\frac{q_\mu^2 \epsilon(\epsilon+1)}{2\omega^2}}\, \cos\phi\, \sigma^L \right.$$

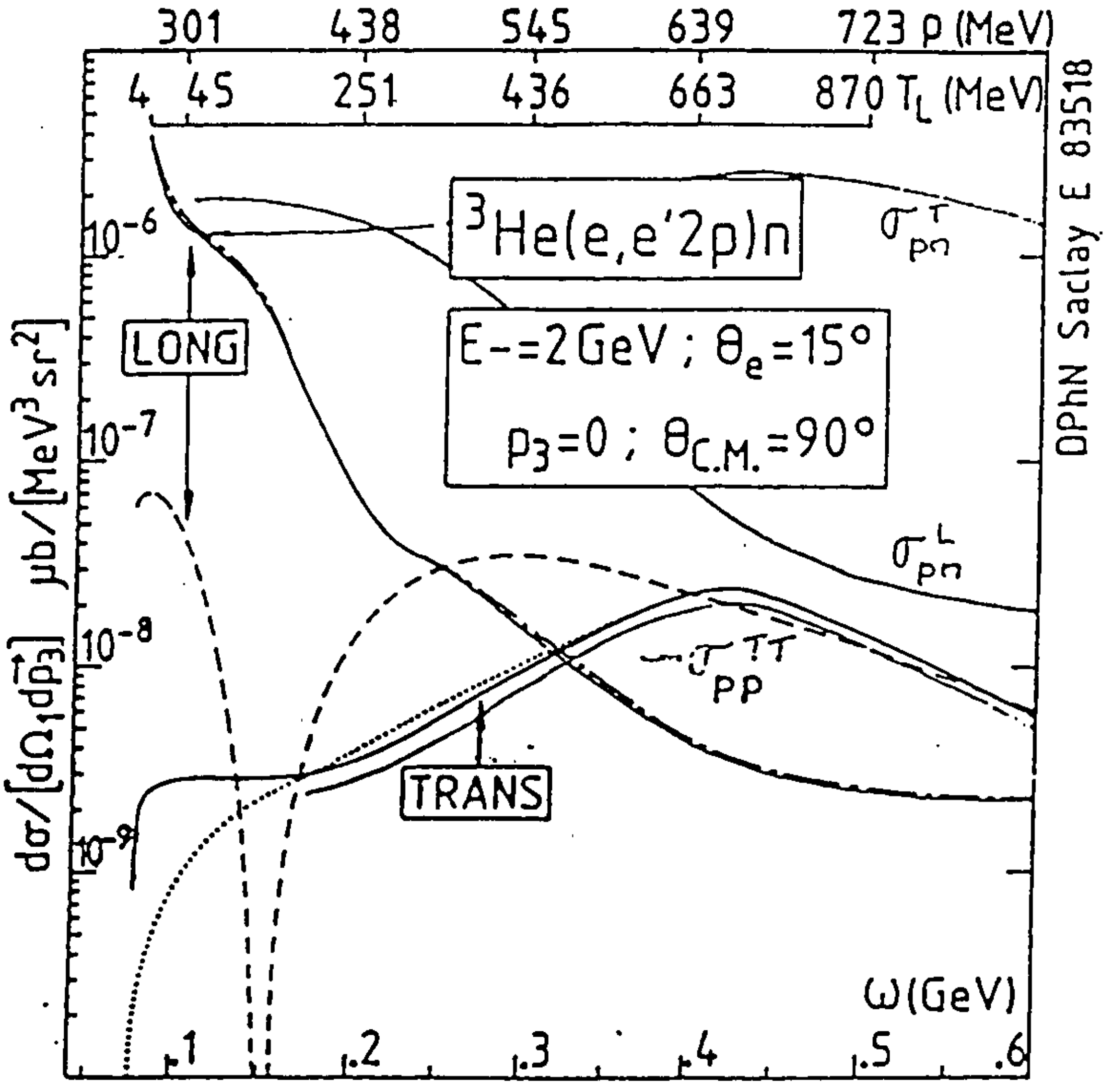
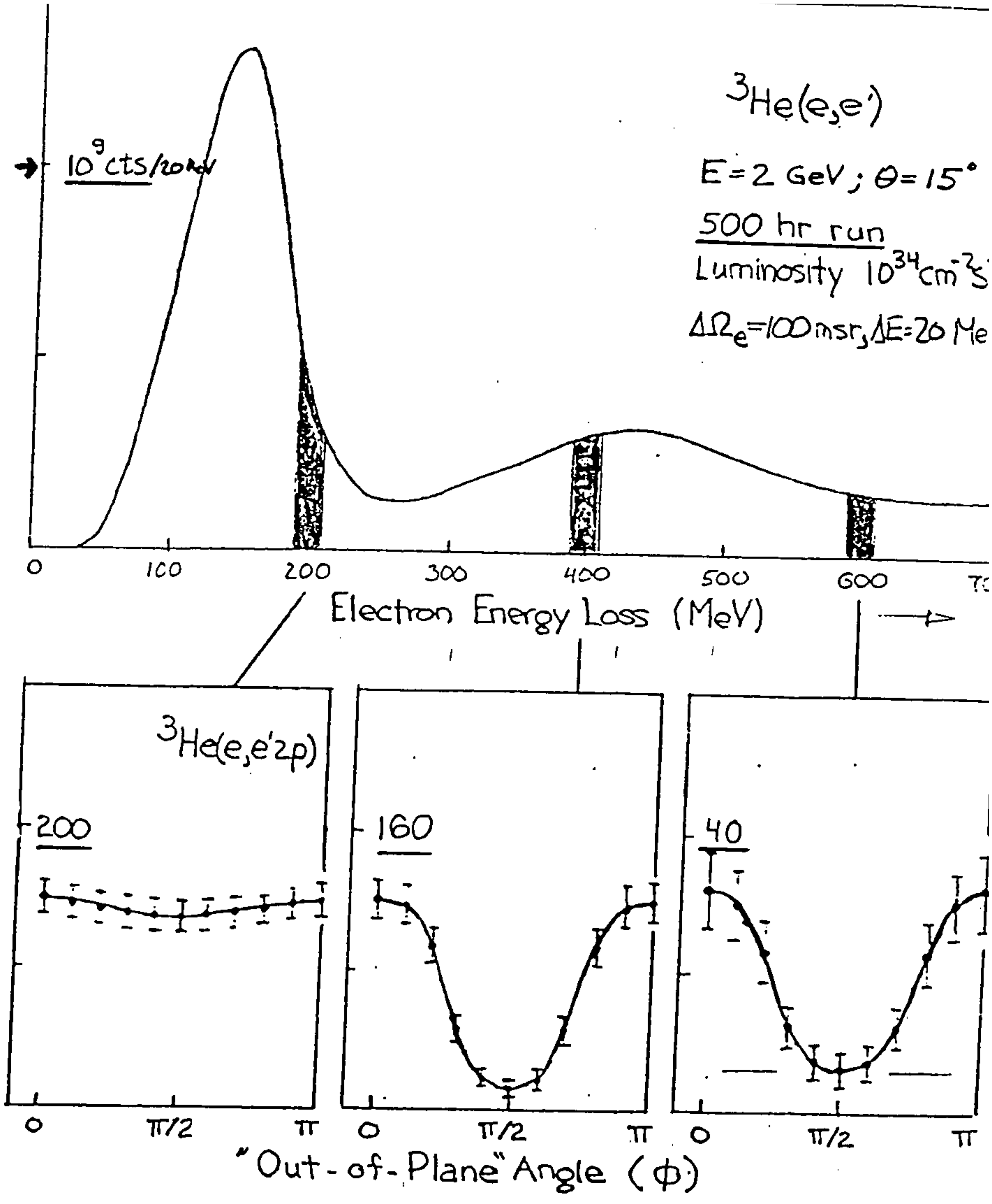


FIGURE 1.



$$\sigma = \Gamma_v\left[\sigma_T + \varepsilon\sigma_L + \varepsilon\cos(2\phi)\sigma_{TT} + \sqrt{\frac{Q^2\varepsilon(\varepsilon+1)}{2\omega^2}}\cos(\phi)\sigma_{LT}\right]$$

FIGURE 2.

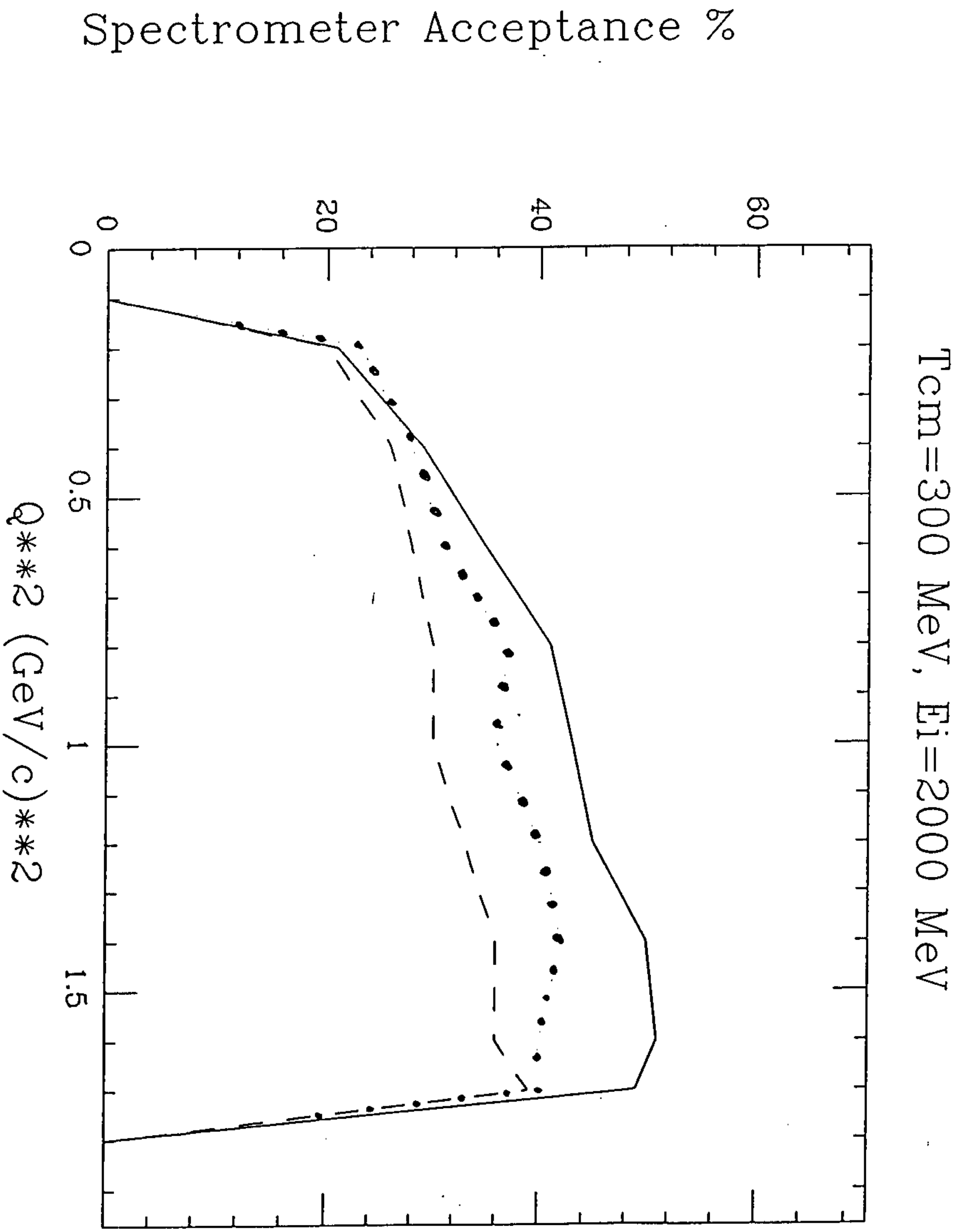

Tcm=300 MeV, Ei=2000 MeV
Spectrometer Acceptance %
Q**2 (GeV/c)**2
0
20
40
60
0
0.5
1
1.5

FIGURE 3.

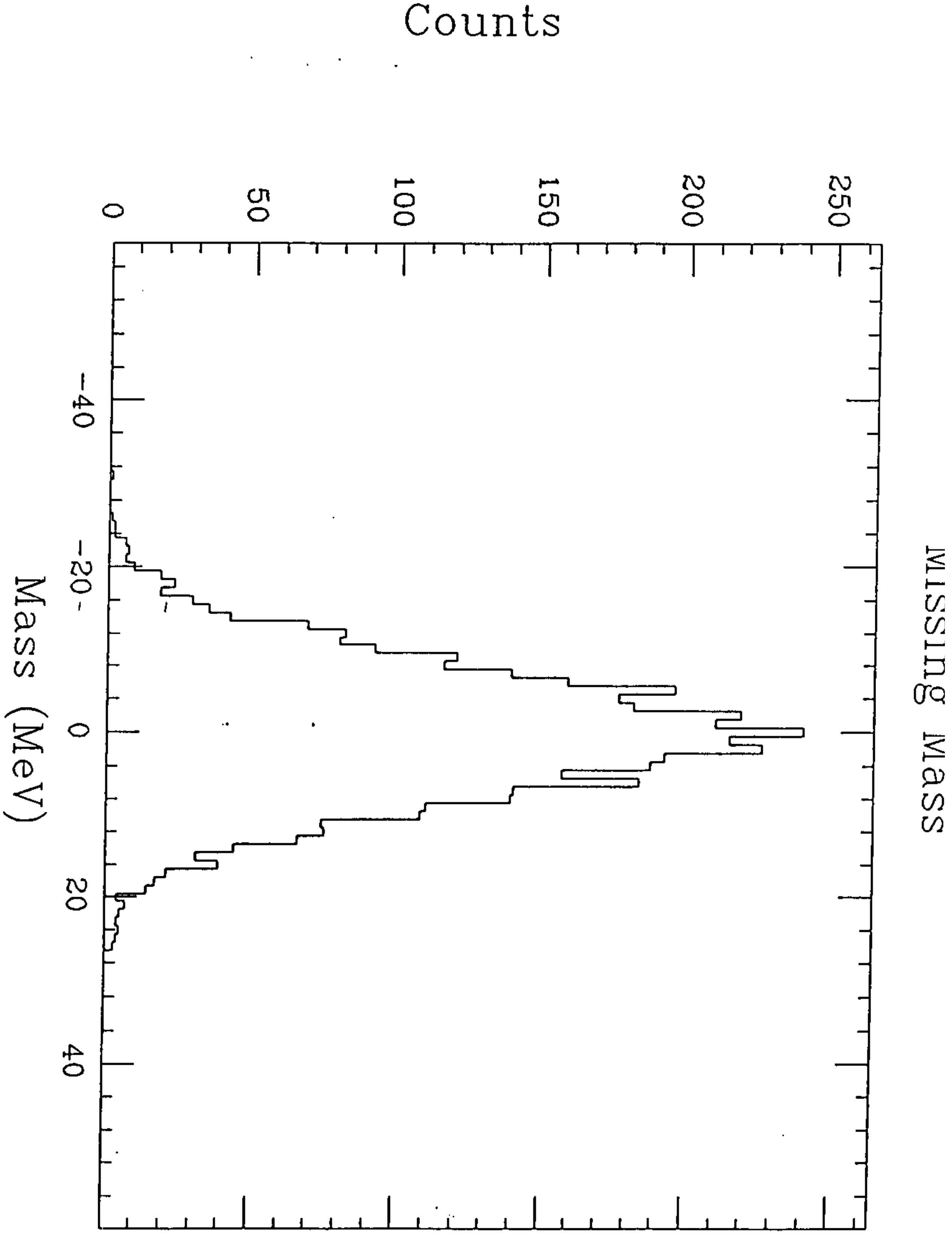


FIGURE 4.

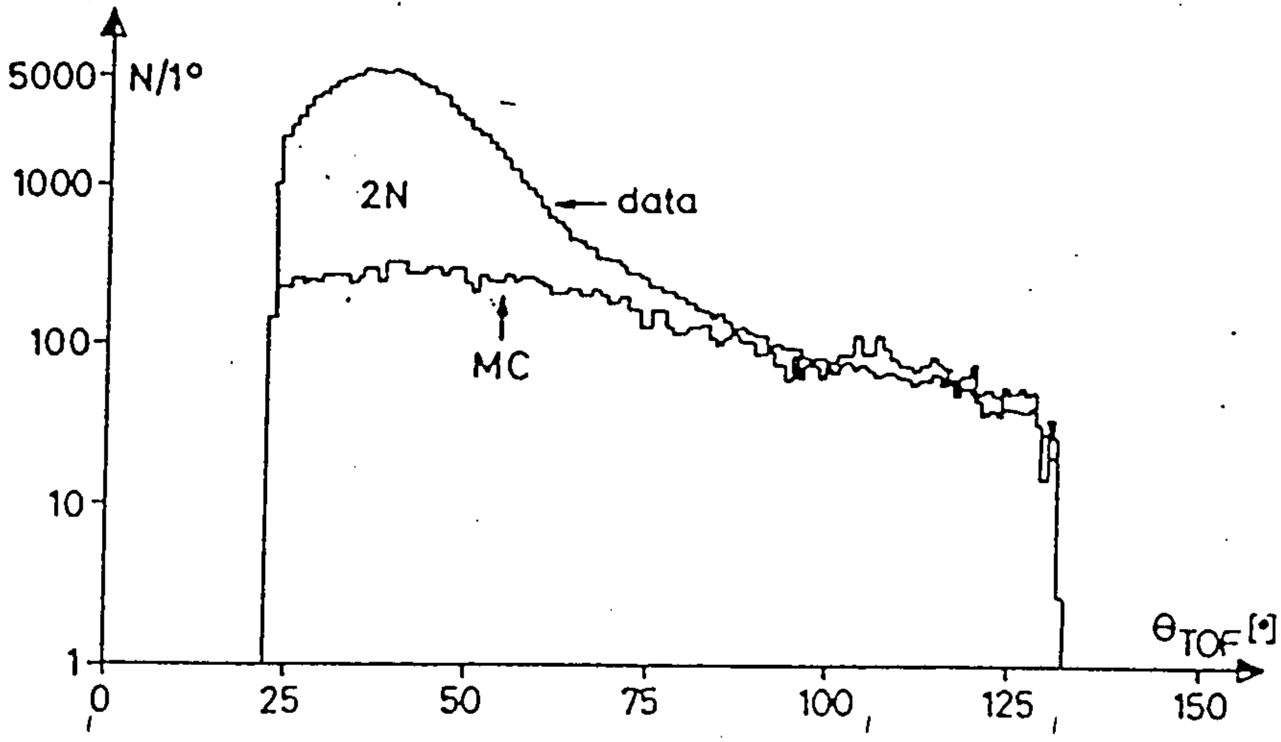


FIGURE 5.

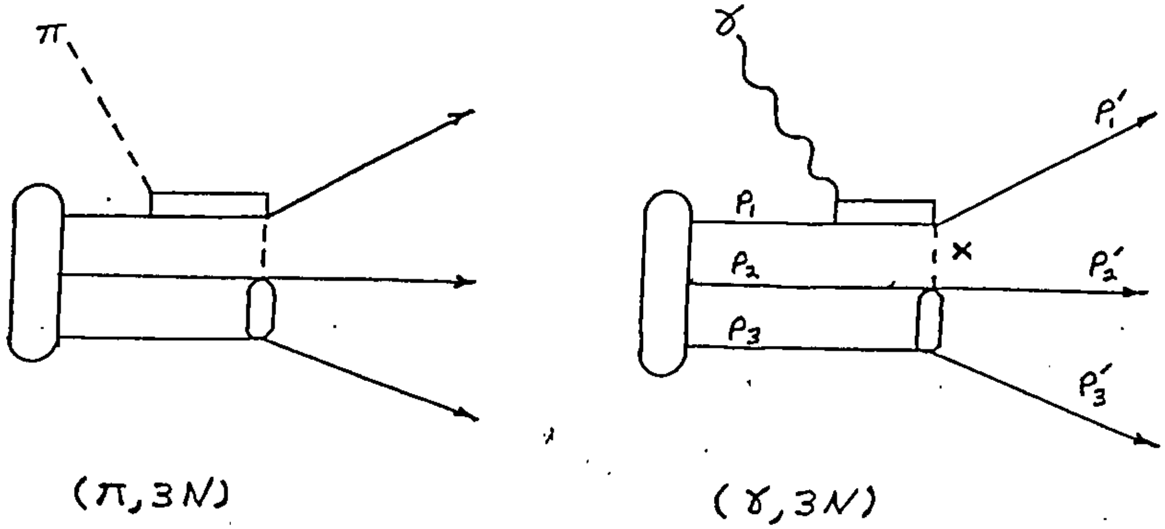


FIGURE 6.

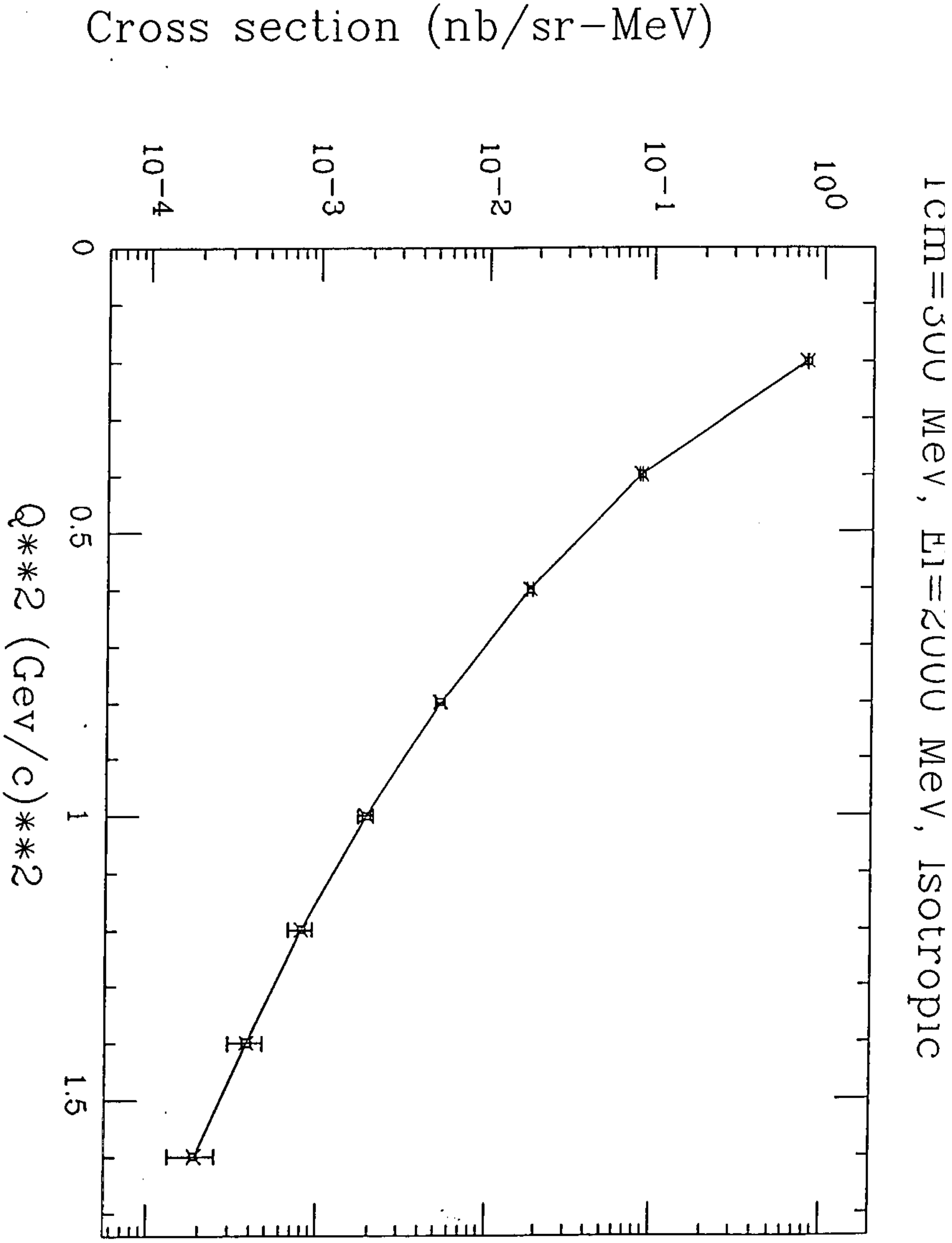

Tcm=300 MeV, E1=2000 MeV, Isotropic
Cross section (nb/sr−MeV)
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
0.5
1
1.5
Q**2 (Gev/c)**2

FIGURE 7.

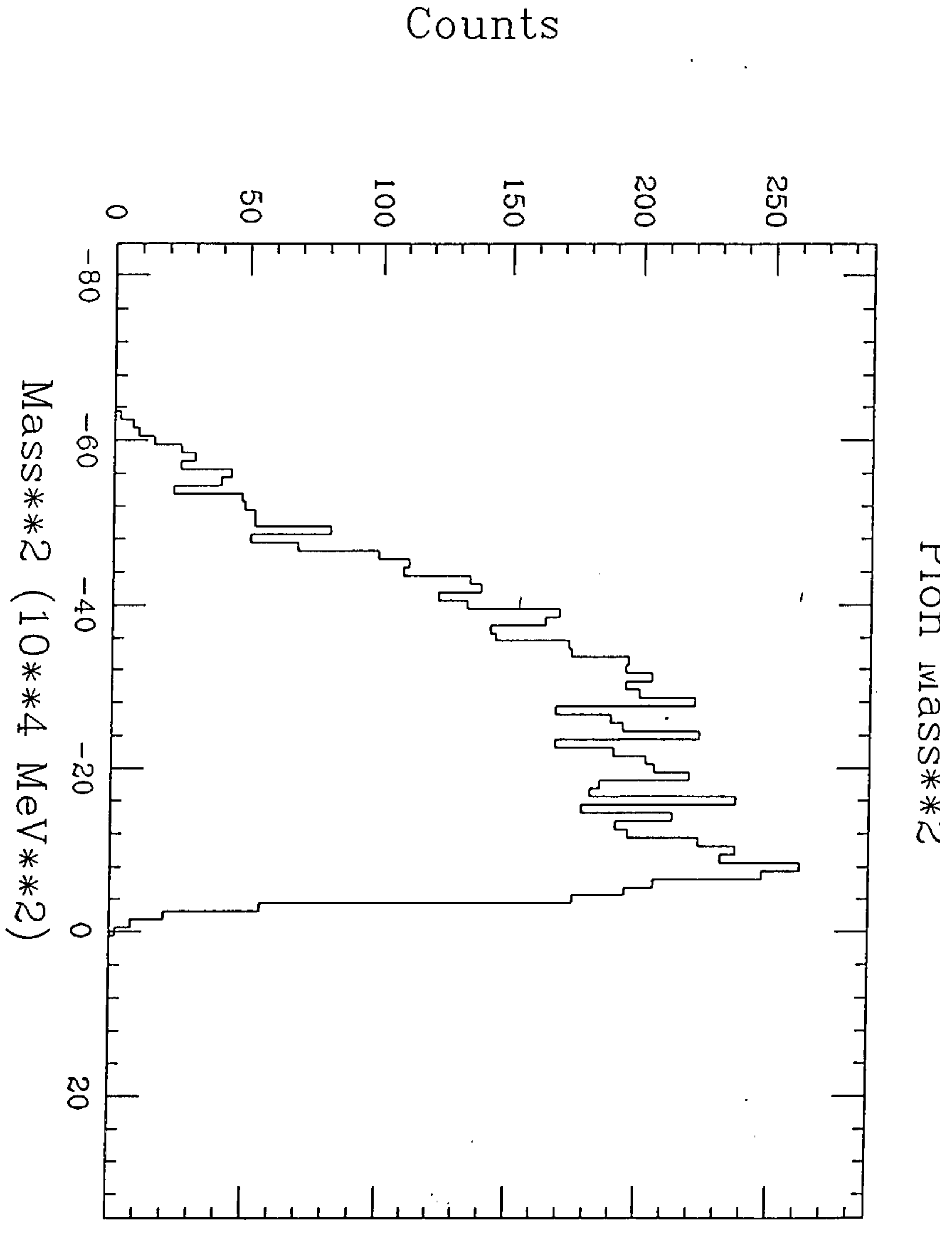

Pion Mass**2
Counts
0
50
100
150
200
250
Mass**2 (10**4 MeV**2)
−80
−60
−40
−20
0
20

FIGURE 8.

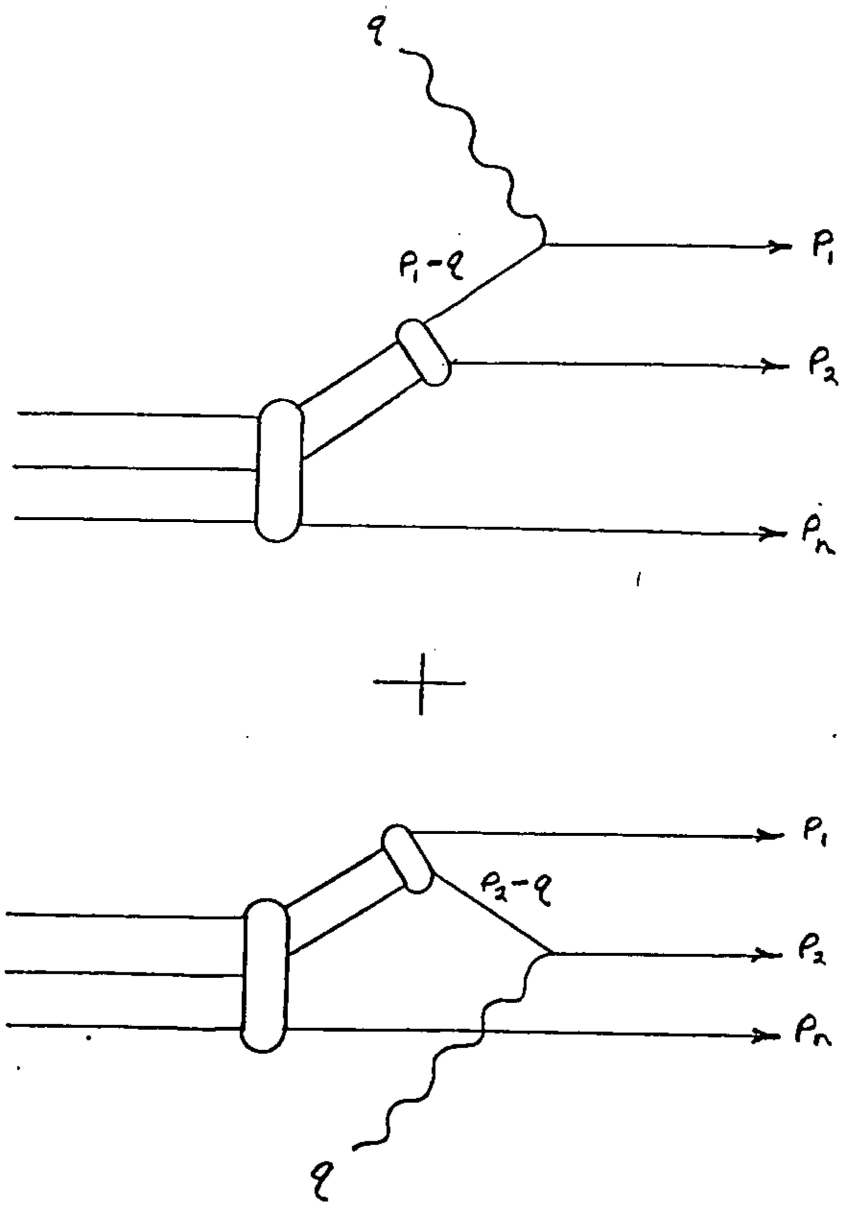


FIGURE 9.

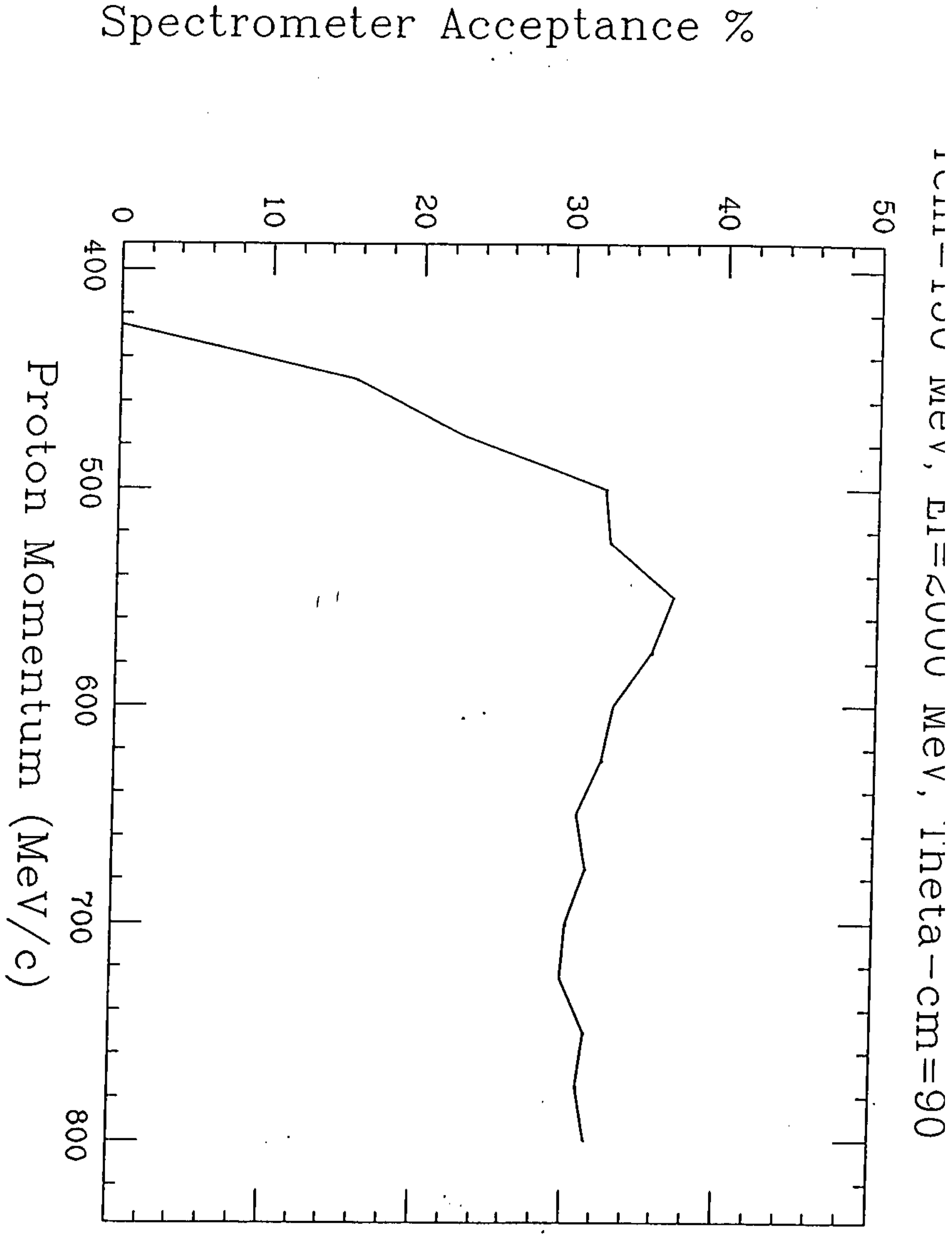

Spectrometer Acceptance %
MeV, Ei=2000 MeV, Theta-cm=90
0
10
20
30
40
50
400
500
600
700
800
Proton Momentum (MeV/c)

FIGURE 10.

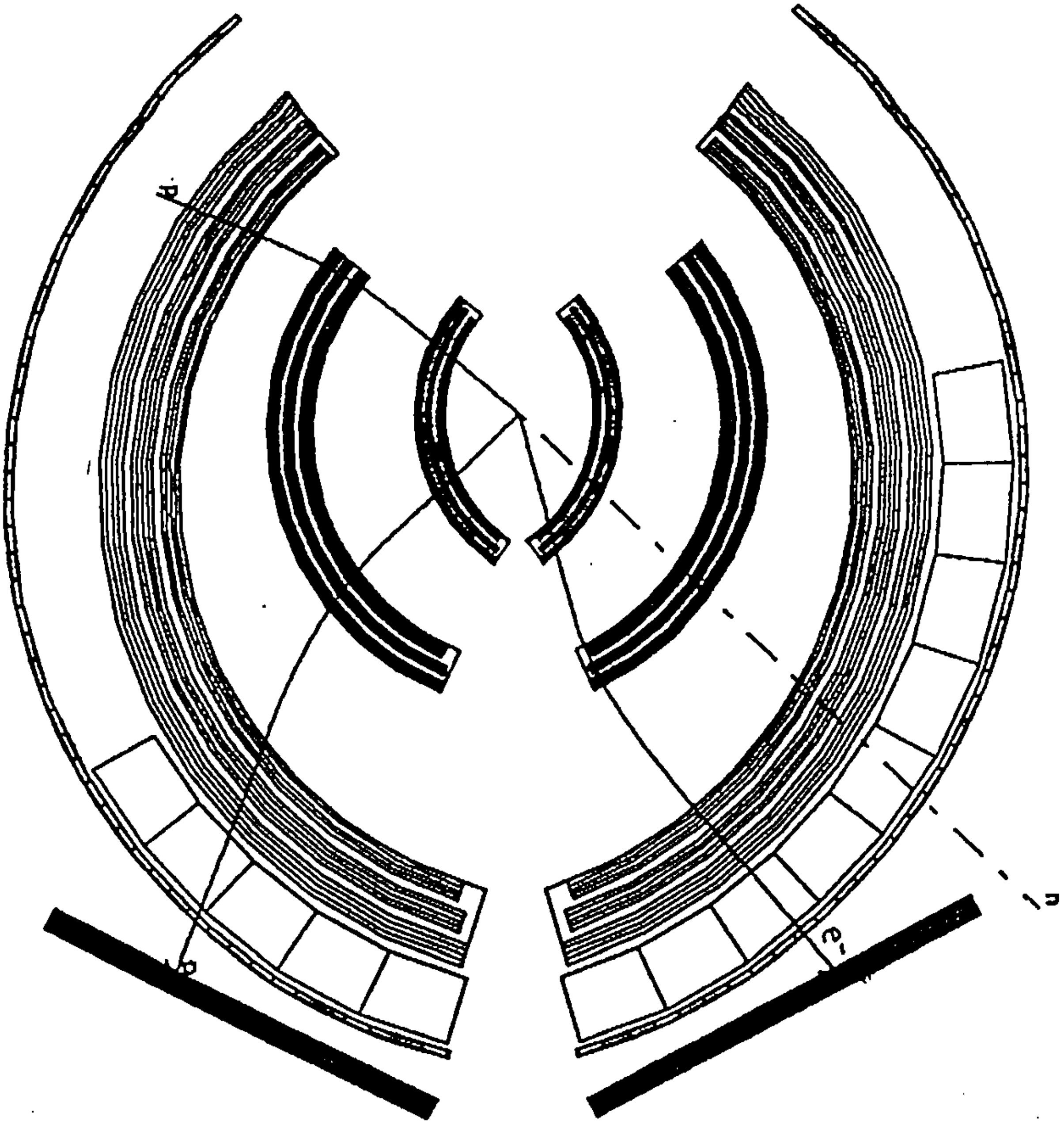


FIGURE 11.

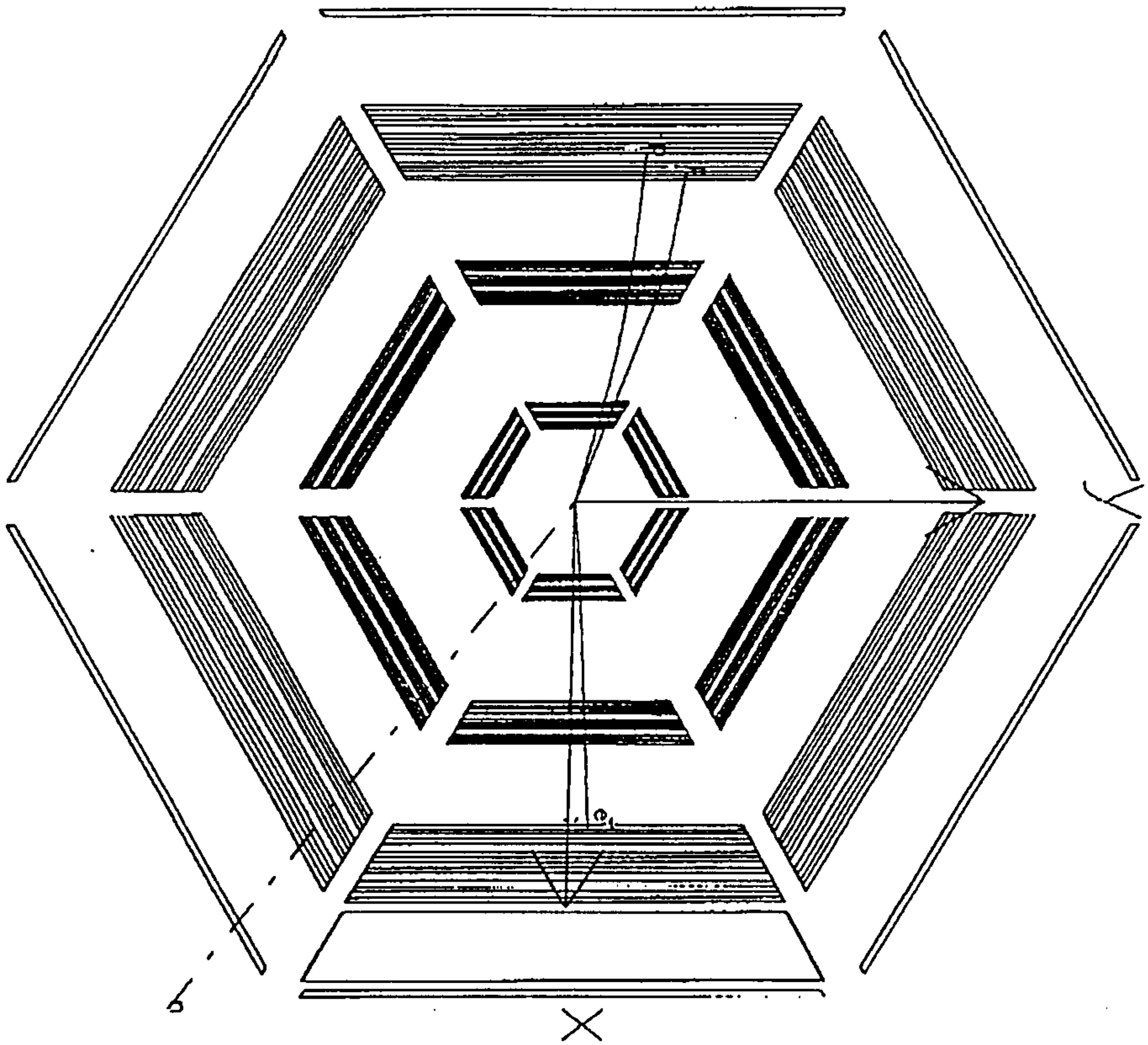


FIGURE 12.

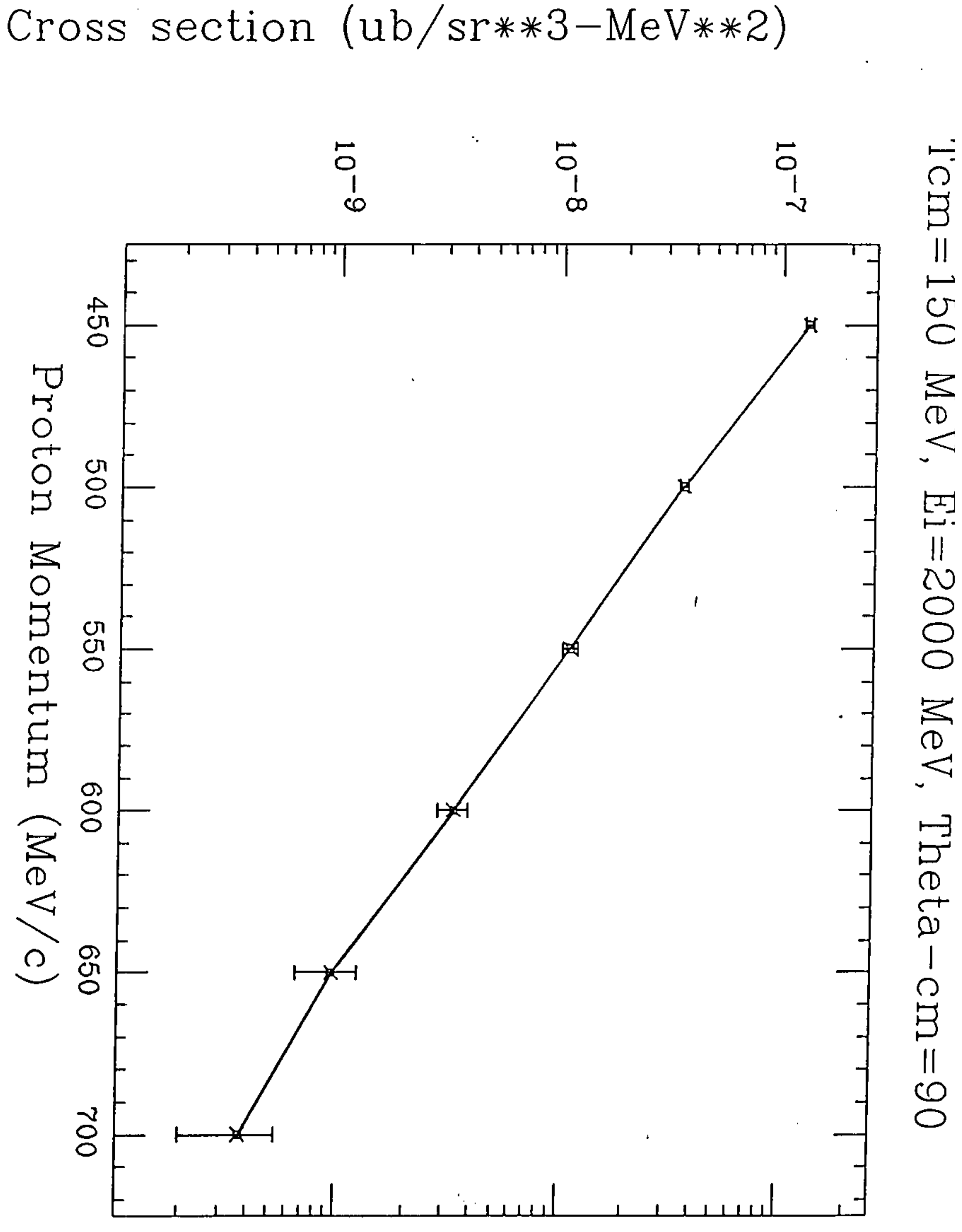

Tcm=150 MeV, Ei=2000 MeV, Theta-cm=90
Cross section (ub/sr**3-MeV**2)
10^{-7}
10^{-8}
10^{-9}
450
500
550
600
650
700
Proton Momentum (MeV/c)

FIGURE 13.

Physics Motivation for ee'2N

F. W. Hersman

Mean field theories of nuclear structure provide a partially successful description of many physical observables. Experimental agreement with predictions for ground state properties, structure of inelastic states, and quasielastic scattering of nucleons in the continuum is obtained at the 50% to 60% level. Exploring the extent of this agreement has dominated much of experimental nuclear physics.

More recently the focus has shifted to examining the 50% disagreement. Meson-exchange currents and ground state correlations are visible in elastic scattering from light and heavy nuclei, respectively. Inelastic scattering, particularly to high spin states, is best explained by partially filled orbitals. The inclusive quasielastic longitudinal sum rule is quenched. Exclusive studies of proton knockout to discrete final states reveal similar partial occupation.

Inclusive and exclusive reactions away from one body kinematics, however, show enhanced strength. Certainly the filling of the dip region, between the quasielastic nucleon and delta knockout, is the most pronounced effect. At the quasielastic peak the transverse scaling function starts to dominate the longitudinal part. More exclusive studies of the quasielastic and dip regions reveal that the additional transverse yield lies in the higher missing energy region of the proton knockout spectral function. This excess reaction strength corresponds to the additional contributions to the structure of nuclei beyond the one-body mean field picture.

The challenge of future exclusive studies is to characterize the reaction channels of the nuclear continuum. Multi-particle processes are important throughout the region of the quasielastic peak and out to higher energy transfers. Other multi-particle knockout channels exist as well. The theoretical goal will be to interpret the observables. A central theoretical issue is to cast the problem in terms of the relevant degrees of freedom. The contributions to the structure of the ground state wave function, including nucleonic and mesonic constituents, can be identified and the strong interaction that acts between them can be quantified.

We propose to measure two nucleon correlations and the effective interaction in the nuclear medium. Specifically, we propose to measure multi-particle final states with electron scattering off ^{3}He and ^{12}C at 2.0 GeV incident energy. In addition, we will take data on carbon at 1.0 GeV. These measurements will be supplemented by electron scattering data on deuterium from other programs which investigate the fundamental two-body interaction. The measurements are designed to determine correlation effects through different spin-isospin channels, meson-exchange currents in the electromagnetic operator, final-state-interaction (FSI) effects, and three-body interactions. A complete kinematic study is proposed, covering an extended range of momentum transfer, energy loss, virtual photon polarization, correlation momentum, outgoing particle opening angle, invariant mass in the pair center of mass, and initial momentum of the pair in the A–2 system.

In general, nuclei are subject to nucleon-nucleon correlations through various channels. Protons and neutrons can interact through the spin-isospin (S=1,I=0) channel and (S=0,I=0) channel. The quark model calculation of Mulders suggest that the first is expected to dominate at lower energies, while the latter comes in at higher energies. The interaction can be mediated by both neutral and charged mesons, so the electromagnetic coupling can involve meson exchange currents. The proton-proton correlations, on the other hand, must have (S=0,I=1) as the dominant channel, and the interaction is mediated only by neutral mesons. Quark models therefore suggest that these correlations come in at higher energy transfers. The exclusivity of the reaction on heavier nuclei can help separate the final state spin and isospin, by identifying the character of the pair that was knocked out.

Nucleon-nucleon correlation structure models would suggest that the strength would follow different kinematics. In this picture, the energy required to remove a correlated proton is the kinetic energy provided to that proton plus the kinetic energy required by the correlated proton, whose momentum is the missing momentum. Semi-exclusive (e,e'p) measurements taken at Saclay on ^{3}He and oxygen show enhance strength for kinematics where the missing energy is just the missing momentum squared divided by twice the mass of the nucleon, substantiating this picture. The strength diminishes at higher correlation momentum, following the correlation function. A search for proton-proton knockout strength at higher energy transfers as a function of correlation momentum could bear on the relative validity of the quark and nucleon pictures.

The presence of correlated protons in the initial state is expected to dominate the longitudinal response. Since the protons are paired in a zero spin state, the contribution of these initial state correlations to the transverse response is suppressed. On the other hand nucleon pairs in motion give rise to convection currents in the transverse coupling. These currents signify interactions with a third body, selecting out a channel to explore three body forces. Whether that third body emerges in heavier nuclei can be determined either by direct observation or by high missing energy in the reaction. In the three body system, this reaction will simply be in the high recoil momentum part of the phase space.

Observation on the deuteron allows determination of proton-neutron correlations in the (S=1,I=0) channel cleanly, including complete out-of-plane determinations. Having a measurement of the fundamental two-body interaction could be crucial for disentangling the two-body interaction in the nuclear medium. For understanding final-state-interaction effects, in particular, contributions to the final state distortions coming from the participating two nucleons may be disentangled from that of neighboring nucleons if the reaction can be studied as a function of nuclear size.

Two nucleon knockout reaction will be observed under the delta knockout region. Non-resonant structure effect continue up to higher inelasticity, but additional processes will come in as well. Resonant delta production can be followed by decay and reabsorption resulting in resonant two nucleon knockout, a process not allowed in free space, and suppressed in very light nuclei. Also the resonant contribution will be transverse, while the longitudinal contribution to the non-resonant piece will survive, allowing separation. Studies as a function of nuclear size can explore damping processes involving other nucleons.

The delta production reaction will be studied on the proton in the resonance program. Certainly the form factor of resonance production will identify spatial distributions of nucleon excitation modes. We include the reaction $(e, e'p\pi)$ in this study because of its close relationship to the $(e, e'pp)$ reaction in the delta region. The FSI of deltas electroproduced in the medium is very strong, much stronger that FSI between nucleons. Through the FSI, one is likely to be able to disentangle the baryon-baryon interaction between nucleons and deltas. Particularly useful would be to incorporate the lighter nuclei, where recoiling protons could identify neutral delta production on the neutron. Comparison of isospin ratios has proven particularly useful in understanding the reaction products of pion scattering studies. Having similar information on electroproduction studies would be similarly useful.

To sum, we propose to characterize the electromagnetic nuclear response in the region of multi-particle knockout. The information will contribute to our understanding of nuclear structure including the nucleon-nucleon correlation function, help to disentangle the relevant degrees of freedom of the nuclear many-body system, and pin down the form of the strong interaction at short range. The contributions to the electromagnetic coupling will be isolated by studying these reactions as a function of virtual photon polarization through different beam energies, nuclear size, and spin-isospin state.