



# MCEEP

## Monte Carlo for Electro-Nuclear Coincidence Experiments

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**Abstract:** This manual describes the Monte Carlo computer program, MCEEP, designed to simulate coincidence (e,e'X) experiments by averaging theoretical models over an experimental acceptance. MCEEP runs under both the VMS and Ultrix operating systems. The program provides for the analysis of measurement uncertainties so that the effects of various systematic errors can be evaluated. This document describes how the program functions and also serves as a user's manual. In addition, simple procedures are given which allow the user to modify the code so that new histograms and/or physics models can be incorporated.

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# Chapter 1

## MOTIVATION

Coincidence ( $e, e'X$ ) experiments, in which an emerging hadron is detected in coincidence with a scattered electron, can provide information which is not revealed by inclusive ( $e, e'$ ) experiments where only the scattered electron is detected. In addition to elucidating the single-particle character of nuclei, coincidence experiments can, by restricting the final state, distinguish among various aspects of the reaction such as non-nucleonic effects (Meson Exchange Currents and Isobar Configurations for example) and 2-body correlations, etc. These experiments have played an important role in our understanding of the nucleus and are likely to become even more important with the advent of high duty factor electron accelerators.

Separation of the coincidence cross section into the various electromagnetic response functions can provide very detailed and important information since various aspects of the reaction mechanism are expected to reveal themselves to different extents in these response functions. However, because of the typically large error magnification inherent in determining response functions from measured cross sections, their precise extraction requires the control of systematic errors to a high degree. In particular, at forward electron angles, where many measurements are expected to be performed (to maximize the counting rate as well as the virtual photon longitudinal polarization lever arm in L/T separations) the cross section is extremely sensitive to variations in the electron scattering angle. These extreme variations coupled with the relatively large experimental acceptances needed to attain high statistical precision necessitate an accurate folding of theoretical models over the appropriate acceptance in order to have meaningful comparisons with data. Thus, it is not generally adequate to merely compare a theory evaluated at the central kinematics with acceptance averaged data. With this in mind and with emphasis on general applicability to any coincidence setup the computer code MCEEP (Monte Carlo for (e,e'p)) was written. Although, the program (and its name) were initially created with ( $e, e'p$ ) in mind, MCEEP is applicable to any single hadron emission experiment provided the appropriate physics routines are incorporated.

This document describes the procedure used by MCEEP in computing physical observables based on a variety of physics models. It also serves as a user's manual describing the input file structure, output options and simple prescriptions for adding new histogram variables or physics models.

## Chapter 2

### INTRODUCTION

MCEEP employs a uniform random sampling method to populate the experimental acceptance. This method differs from a "true" Monte Carlo which generates events distributed according to a predetermined weighting function. Although the latter method more closely resembles the actual experiment and avoids the need to keep track of weights for each event, it becomes unwieldy for the large number of dimensions needed to describe the experiment in its full generality. For example, in addition to the nine variables required to describe the incident beam, scattered electron and emerging nucleon there are other dependences such as the beam polarization and target polarization as well as the implicit dependence of the cross section on the beam-target interaction point. In addition, in contrast to MCEEP's method, the importance sampling technique requires a large number of events in order to obtain precise statistics for small cross sections in the presence of a dominant contribution.

An event is defined as any combination of variables which completely specifies the reaction in the laboratory. For each event, weights which correspond to the relevant observables (cross sections, polarizations, etc.) are computed according to a user selected physics model. The histograms represent the accumulation of these weights. Any of the weights corresponding to the various physical observables can be attached to a given histogram by selections made within the user input file.

The program is written in a modular form allowing easy incorporation of specialized subroutines. This is particularly important for the cross section routines so that, with minimal effort, new theoretical models can be introduced as they become available. The kinematics are kept general so that variations with respect to any variable can be examined and experiments with arbitrary geometries (such as out-of-plane with either a raised spectrometer or beam swinger) can be considered. In addition, MCEEP allows for a general 3-D beam-target interaction region so that the effects of extended targets and rastered or defocused beams can be evaluated.

MCEEP can perform calculations for elastic scattering,  $(e,e'X)$  to bound states of the residual system or  $(e,e'X)$  in the (unrestricted) continuum according to the user's choice. For elastic scattering, MCEEP performs a two-dimensional integral over the electron solid angle. The electron final energy as well as the nuclear recoil momentum are all constrained kinematically. For elastic scattering the user may choose to enforce the acceptance cuts of the hadron arm to simulate an  $A(e,e'A)$  experiment, or leave the recoil kinematically unrestricted (i.e. single-arm elastic scattering). For the bound state, MCEEP performs a five dimensional integral, wherein the ejectile momentum is calculated from the bound state missing mass (specified in the input file) and the values of the other five randomly selected kinematical variables (the electron momentum and in-plane and out-plane angles and the ejectile in-plane and out-of-plane angles). For the continuum case, the ejectile momentum is also randomly selected and the missing mass is then calculated event-by-event. Of course, bound state scattering can be effectively calculated by choosing the

continuum option with a narrowly peaked missing mass distribution function. However, this is usually a very inefficient method since most events will correspond to the tails of the distribution (depending upon how sharply peaked it is) and hence will contribute very little to the integral.

The program provides for simulation of various detector/spectrometer systems by allowing the user to specify a series of "spectrometer elements" which act on a Transport<sup>[1]</sup> vector based on the laboratory coordinates directly sampled in the Monte Carlo event loop. Analysis of uncertainties is accomplished by allowing the user to offset a given Transport ray coordinate or to smear it with a gaussian resolution function. Several other types of elements are also available including multiplication of the Transport vector by a matrix, drifts and rotations in field-free regions and spin precession through a series of magnetic elements. In addition, both histograms and cuts can be defined at any point along the spectrometer line. The cuts can be attached to particular histograms defined at any location or can be applied globally. Note that the so-called "spectrometer" elements are not restricted to magnetic devices but can also be used to simulate simple detector systems, such as for neutron detection experiments, etc.

Output of MCEEP consists of a set of histograms representing dynamical quantities (polarizations, cross sections or the actual yield) as a function of various kinematical variables. The physics observable as well as the kinematic variable are selected by the user via an input file. In addition, the user can specify a set of cuts to be applied to either all histograms (global cuts) or to individual histograms (specific cuts). Histograms of Transport ray coordinates can also be requested in the spectrometer analysis section of the input file. Finally, MCEEP produces a summary file which consists of a formatted display of the user input, histogram summary tables and various statistics which reflect the population of the kinematical variables.

In the next chapter the general layout of the program as well as the main subroutines employed by MCEEP are described. The remaining chapters discuss various aspects of the program in detail.

## Chapter 3

# GENERAL DESCRIPTION OF MCEEP

### 3.1 "Event" Generation and Coordinate Systems

An event is chosen by randomly selecting a momentum and two orientation angles for each particle (the scattered electron and emerging hadron) somewhere within the experimental acceptance. In the most general case, the beam-target interaction point is also chosen at random somewhere within the target volume (consistent, of course, with the beam profile). The angular apertures of the spectrometers can be either rectangular or elliptical. The angles are actually chosen by specifying *spatial* coordinates (one along  $X$  and one along  $Y$  where these coordinates are defined according to the Transport notation) within each of the two apertures. This combined with the beam-target interaction coordinates specify the actual orientation angles relative to a fixed system in the laboratory for each of the two emerging particles. This method of sampling is very efficient since it guarantees that the particles lie within the apertures even for extended targets. In contrast, if one selects *angles* at random (relative to a fixed coordinate system in the laboratory) there is no guarantee that for any origination point within the target the resulting particle will lie within the solid angle defining aperture. Finally, the user may elect to give the incident beam a spread in energy or angle in which case these quantities are chosen randomly according to a prescribed (gaussian) distribution with mean values equal to the nominal input values.

All quantities are specified relative to one fixed coordinate system. Having a fixed coordinate system simplifies the calculation of various kinematical quantities through vector operations. The system is defined as the "laboratory" coordinate system. Thus, the nominal beam orientation defines the  $Z$  axis (in the case of a beam swinger "nominal" means the horizontal projection of the beam direction - i.e. in the plane of the laboratory floor). The  $Y$  axis points vertically upward (relative to the laboratory floor) and  $\hat{x} = \hat{y} \times \hat{z}$ .

From the randomly selected coordinates (hereafter referred to as the "laboratory coordinates" since they refer to a fixed coordinate system in the laboratory), the coordinates in the "Transport" system can be computed. This is convenient for incorporating the properties of spectrometers or detection systems into the analysis. For example, it may be of interest to examine the distribution of events at the focal plane of a spectrometer since this has direct relevance for the detectors. Also, as will be discussed in detail later, the effects of uncertainties and errors can be evaluated by introducing offsets and smearing into the appropriate Transport coordinate. The method of incorporating detection systems and various measurement uncertainties involves starting with the Transport vector at the target for both arms and applying functional mappings (currently only multiplication by a 1st order matrix is supported), offsets and resolution smearing to this coordinate vector. The final element in the spectrometer analysis input (see the chapter on spectrometer analysis for more details) must convert the resulting coordinate vector back to the Transport vector at the target. Thus, a closed loop is formed starting and ending at the target Transport vector. From this "affected" Transport vector the laboratory coordinates can again be determined. From the laboratory coordinates, "physical variables" which are more convenient for the calculation of dynamical quantities are computed.

### 3.2 Recoil Polarization Observables

In addition to cross sections, MCEEP provides histograms of recoil polarization observables. The three components of the emerging hadron's polarization can be calculated using various theoretical models. Since the polarizations are computed relative to the reaction plane (i.e. the plane containing  $\vec{q}$  and the emerging hadron) the orientation of which changes from event to event, the resulting histograms represent an average of the polarization components over a range of orientations in the laboratory. In fact, in parallel kinematics, the orientation of the reaction plane sweeps out the full  $2\pi$  angular range as the direction of the emerging hadron describes a cone about  $\vec{q}$ . Thus, for small  $\theta_{pq}$ , polarization components perpendicular to  $\vec{q}$  will average to zero. It is therefore necessary to define a coordinate system which is fixed in the laboratory to which the polarization components can be referred. A coordinate system tied to the hadron spectrometer is most convenient since one can then compute effects of the spectrometer on these components (from precession of the spin through the spectrometer magnetic elements) and can examine the distribution of events in a polarimeter which is also fixed relative to the spectrometer.

We define three right-handed coordinate systems,  $L$ ,  $R$  and  $S$ , all of which are at rest with respect to the laboratory, although  $R$  is event-dependent. These systems will now be defined.

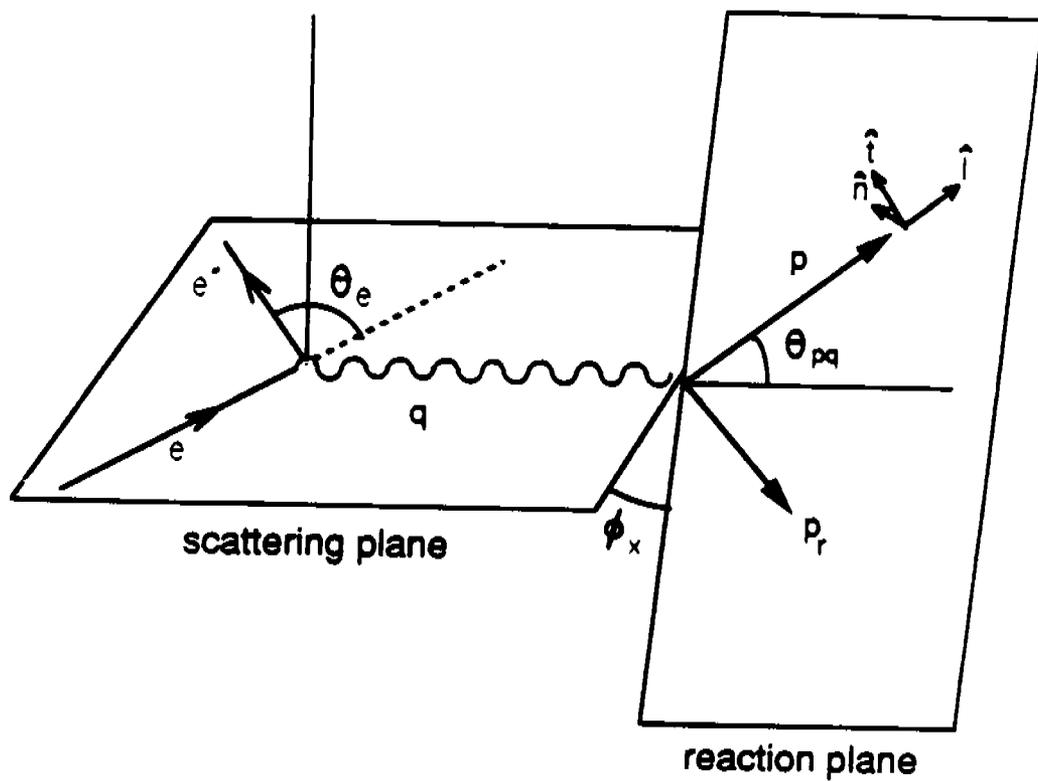
" $L$ " denotes the usual "laboratory" frame (defined earlier). The  $Z$  axis points along the nominal beam direction (in the plane of the laboratory floor), the  $Y$  axis points vertically upward and  $\hat{x} = \hat{y} \times \hat{z}$ . We define three unit vectors,  $\hat{l}_1$ ,  $\hat{l}_2$  and  $\hat{l}_3$  pointing along the  $X$ ,  $Y$  and  $Z$  "laboratory" axes respectively.

" $R$ " denotes the "reaction" frame. This system is the preferred frame for the calculation of the polarization observables. Here, the  $Z$  axis points along the hadron momentum, the  $X$  axis is normal to the reaction plane (i.e. the plane containing  $\vec{q}$  and the hadron momentum) and the  $Y$  axis direction is given by  $\hat{z} \times \hat{x}$ . By convention, the  $X$  axis points upward for coplanar kinematics with  $\phi_z = 0$ . (Note that  $\phi_z = 0$  corresponds to hadrons forward of  $\vec{q}$ .) We then define three "reaction" frame unit vectors,  $\hat{r}_1$ ,  $\hat{r}_2$  and  $\hat{r}_3$ , corresponding to the usual  $n$  (normal),  $t$  (transverse) and  $l$  (longitudinal) polarization components respectively (as shown in Figure 1). Note that with these conventions,  $\hat{r}_1$  and  $\hat{r}_3$  point along the  $X$  and  $Z$  coordinate axes respectively, whereas  $\hat{r}_2$  points in the  $-Y$  direction. Thus, although the  $X$ ,  $Y$  and  $Z$  coordinate axes define a right-handed system, the three unit vectors,  $\hat{r}_1$ ,  $\hat{r}_2$  and  $\hat{r}_3$  form a left-handed system. The polarization vector, referred to  $R$  can be constructed as:

$$\vec{P} = p_n \hat{r}_1 + p_t \hat{r}_2 + p_l \hat{r}_3.$$

With the above conventions:

$$(R \text{ frame vectors}) \begin{cases} \hat{r}_1 = \vec{q} \times \vec{p} / |\vec{q} \times \vec{p}| \\ \hat{r}_2 = \hat{r}_1 \times \hat{r}_3 \\ \hat{r}_3 = \vec{p} / |\vec{p}|. \end{cases}$$



**Figure 1.** Kinematics of  $(e, e'p)$  including the coordinate system for the "reaction-frame" polarization observables.

We wish to determine the three polarization components with respect to unit vectors in the  $S$  frame. " $S$ " denotes the "spectrometer" frame, which is fixed relative to the laboratory for a given spectrometer setting (as opposed to  $R$  which depends on the scattering event). This frame is the preferred frame for examination of those quantities directly measured by the polarimeter. Here, the  $Z$  axis points along the spectrometer optic axis from the target, the  $Y$  axis is normal to the spectrometer midplane and the  $X$  axis is in the spectrometer midplane normal to  $Z$ . By convention the  $X$  axis points downward for a spectrometer which bends vertically upward (i.e. along the direction of increasing dispersion) and  $\hat{x} = \hat{y} \times \hat{z}$ . We define three unit vectors in the "spectrometer" system,  $\hat{s}_1$ ,  $\hat{s}_2$  and  $\hat{s}_3$  which point along the  $X$ ,  $Y$  and  $Z$  coordinate axes respectively. These three unit vectors thus define the orientation of the polarization vector at the target relative to the spectrometer. In terms of the spectrometer angles,  $\theta$  and  $\phi$  (where  $\theta$  is the out-of-plane angle and  $\phi$  is the azimuthal angle relative to the beam; note that these angles are not the usual spherical coordinate angles due to the definition of the "laboratory" coordinate system) we can find the components of each unit vector relative to the  $L$  frame. By applying three successive passive rotations the "laboratory" to "spectrometer" rotation matrix can be obtained:

$$\mathcal{R}_{L \rightarrow S} = \mathcal{R}_Z(\theta_{bp}) \mathcal{R}_X(-\theta) \mathcal{R}_Y(\phi)$$

where the subscripts on each matrix on the right-hand side specify the axis of rotation and where positive rotation angles correspond to a coordinate rotation with a positive sense as given by the right hand rule. Here,  $\theta_{bp}$  defines the orientation of the spectrometer bend plane. For a spectrometer which bends vertically upward,  $\theta_{bp} = -90^\circ$ , and  $\theta_{bp} = 0$  for a spectrometer which bends rightward, etc. Note,  $\phi > 0$  corresponds to a spectrometer on the left side of the beam (looking toward the beam dump) and  $\theta > 0$  for a spectrometer raised above the floor. To minimize confusion, the explicit forms of these rotation matrices are:

$$\mathcal{R}_Y(\phi) = \begin{pmatrix} \cos \phi & 0 & -\sin \phi \\ 0 & 1 & 0 \\ \sin \phi & 0 & \cos \phi \end{pmatrix},$$

$$\mathcal{R}_X(-\theta) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \theta & -\sin \theta \\ 0 & \sin \theta & \cos \theta \end{pmatrix}$$

and

$$\mathcal{R}_Z(\theta_{bp}) = \begin{pmatrix} \cos \theta_{bp} & \sin \theta_{bp} & 0 \\ -\sin \theta_{bp} & \cos \theta_{bp} & 0 \\ 0 & 0 & 1 \end{pmatrix}.$$

Now, let  $r_{ij}$  be the  $i^{\text{th}}$  component of the  $j^{\text{th}}$   $R$  frame unit vector referred to the laboratory system,  $L$ . Further, let  $s_{ij}$  be the  $i^{\text{th}}$  component of the  $j^{\text{th}}$   $S$  frame unit vector referred to  $L$ . The components of the polarization vector in the  $L$  frame are then

$$p_i^L = r_{ij} p_j^R$$

where  $j = 1, 2, 3$  for  $p_n$ ,  $p_t$  and  $p_l$  respectively and a sum over repeated indices is implied. Thus, the rotation matrix  $r_{ij}$  gives the components of the polarization vector in  $L$  from the

components in  $R$ . We can then determine the components of  $\vec{P}$  in the spectrometer frame by taking the dot product of  $\vec{P}$ , as given by its components above, with the appropriate spectrometer unit vector also expressed in terms of its components in  $L$ :

$$p_k^S = s_{ik} p_i^L = s_{ik} r_{ij} p_j^R$$

with  $s_{ik}$  as given above in terms of  $\theta$ ,  $\phi$  and  $\theta_{bp}$ . Effectively, the matrix  $s_{ij}$  gives the components in  $L$  from the components in  $S$ . We can define a matrix  $l_{ij}$  which is the inverse of  $s_{ij}$  (or the transpose in this case:  $l_{ij} = s_{ji}$ ) so that:

$$p_k^S = l_{ki} r_{ij} p_j^R.$$

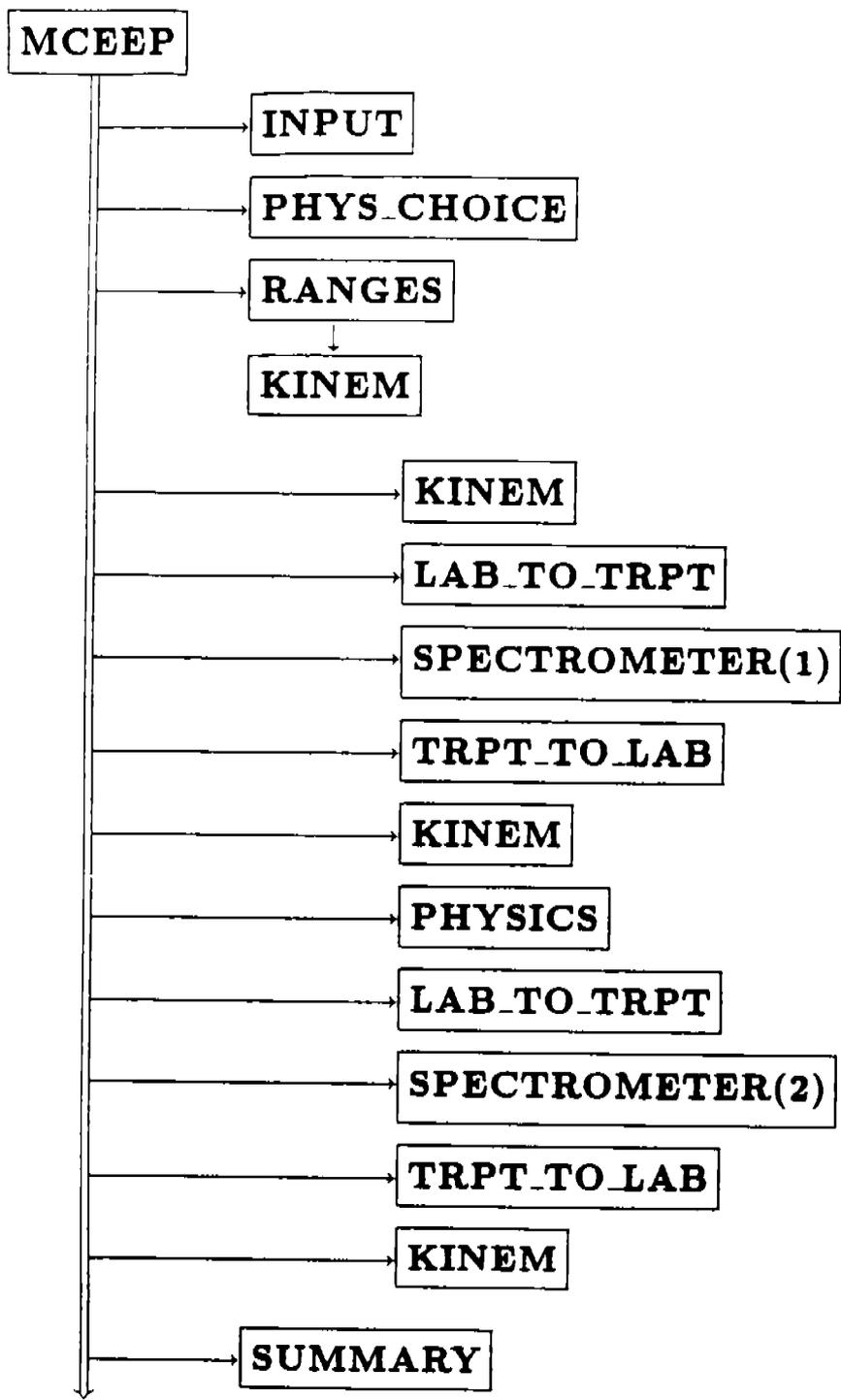
Thus,  $r_{ij}$  gives components in  $L$  from components in  $R$  and  $l_{ij}$  gives components in  $S$  from components in  $L$ . One need only take the matrix product to go from  $R$  to  $S$ .

### 3.3 Layout of the Program

A block diagram of the program is shown in Figure 2. Subroutines are shown to the right of the double arrow and are called in order reading down the page as indicated by the double arrow. Only the main subroutines and those relevant to the present discussion are shown. Subroutines within the main event loop are indented.

At the start of the Monte Carlo event loop, the "laboratory" coordinates,  $q_i$ , for both the scattered electron and the ejectile are chosen randomly. From these coordinates a Transport vector at the target,  $x_i^t$ , is constructed for each arm by subroutine LAB\_TO\_TRPT. Various operations can then be applied to these Transport vectors via the subroutine SPECTROMETER. From the resulting "affected" Transport vectors,  $x_i^t'$ , new laboratory coordinates,  $q_i'$ , are calculated by the subroutine TRPT\_TO\_LAB. All derived kinematical quantities are then calculated from these variables by subroutine KINEM. Note that for this to make sense, the "affected" Transport vectors returned by SPECTROMETER should correspond to the target position. Thus, for example, any Transport matrices applied within SPECTROMETER, should be eventually "undone" by application of their corresponding inverses.

As indicated in Figure 2 there is some apparent repetition within the main event loop in that several subroutines are called twice. This is because subroutine SPECTROMETER affects the kinematics at two levels. As is explained in detail below, some of the spectrometer elements affect only the cross sections while others affect only the kinematic bins for the histograms. This is necessary to account for various types of measurement errors. For instance, spectrometer misalignments do not affect the histogram bins into which the events are placed since these errors are presumably unknown. Rather each bin is effectively weighted by a cross section which reflects the actual kinematics. On the contrary, multiple scattering effects the kinematic bins but not the cross sections since this secondary scattering (for the scattered electron and ejectile) occurs, by definition, after the primary (e,e'X) scattering. Thus, in the first call to SPECTROMETER only those operations which affect the cross sections are applied. After the cross sections are computed by subroutine PHYSICS, the kinematics are reset to their original (i.e. before the call to SPECTROMETER) values. Then SPECTROMETER is called and those operations affecting the kinematic bins are applied. The histograms are updated after the second call to SPECTROMETER.



**Figure 2** Block diagram of the main subroutines called by MCEEP. Subroutines are to the right of the double arrow and are called in order reading down the page. Indented subroutines are within the main Monte Carlo event loop. For clarity, only the main subroutines are shown.

### 3.4 Description of Subroutines

The subroutines are now briefly described in the order in which they are called by the main program.

- INPUT** All input is obtained from the user input file by the subroutine INPUT. All input variables are placed into COMMON blocks within the Fortran INCLUDE file "CMN%D:INPUT.CMN" so that the main routine has access to them. A complete description of the input variables are given in this document as well as in the comment statements within INPUT itself.
- PHYS\_CHOICE** The physics model is chosen within the subroutine PHYS\_CHOICE which is a menu-driven routine. This routine is called only once within MCEEP. PHYS\_CHOICE; in addition to obtaining the user's physics selection, performs any preliminaries such as opening and reading files. Also, if one of the factorized (e,e'N) options is chosen, PHYS\_CHOICE will call subroutine SPECT\_SETUP which allows the user to select a spectral function from a menu and performs any necessary preliminaries.
- RANGES** This subroutine is a preprocessor which provides default ranges for all histograms (other than spectrometer analysis (i.e. Transport) histograms). RANGES is described in more detail in the chapter on histograms.
- KINEM** KINEM performs calculations of all kinematic variables so that they may be histogrammed. Each variable is equivalenced to an element of the array VAR within the Fortran INCLUDE file "CMN%D:VAR.CMN". KINEM is called several times within the program. The first call is initiated by subroutine RANGES so that the default limits for all histogram variables can be determined. KINEM is also called three times within the main event loop. The first call merely calculates the ejectile momentum if the bound state option is selected. For the continuum option, the ejectile momentum is one of the randomly selected variables, whereas for the bound state option this value is calculated from the other randomly selected variables and the specified missing mass. The remaining two calls determine all the kinematic variables, first for the evaluation of cross sections and next for the determination of the histogram channels in which to place the event. The reason for this is explained above and in more detail in the chapter on spectrometer analysis. More details about the kinematic variables are given in the section on adding new histogram variables.
- LAB\_TO\_TRPT** This subroutine returns a Transport vector for a given arm based on the "laboratory" coordinates which are passed to it.

**SPECTROMETER** This subroutine performs various operations on the Transport vectors as specified in the user input file. **SPECTROMETER** also provides for histograms of any Transport coordinate anywhere along the spectrometer line. The various options of **SPECTROMETER** are described in detail later.

**TRPT\_TO\_LAB** This subroutine returns the "laboratory" coordinates based on the Transport vector passed to it (and is thus the inverse of subroutine **LAB\_TO\_TRPT**). Subroutine **KINEM** determines all derived kinematical quantities based on these "laboratory" coordinates.

**PHYSICS** This subroutine calculates cross sections and polarizations according to the selection made via **PHYS\_CHOICE**.

**SUMMARY** **SUMMARY** produces a formatted output of various statistics along with a histogram summary and the input contained within the user input file.

## Chapter 4

### HISTOGRAMMING

The various histogramming options are now described, including the specification of cuts (both global and histogram specific) as well as the preprocessor routine RANGES which finds default limits for each histogram. Transport histograms are not discussed here but are described in the spectrometer analysis chapter.

#### 4.1 Options for Variables

Each histogram consists of some dynamical quantity vs. a kinematical variable both of which are selected by the user. The user specifies any desired histograms via the input file. For each histogram a "weighting" tag which specifies the dynamical variable and an index corresponding to a particular kinematical variable are specified.

In the case of an unpolarized target the coincidence cross section can be written as:<sup>[2]</sup>

$$\begin{aligned}\sigma &= \frac{\sigma_0}{2} \left[ 1 + h(A + \vec{\pi}' \cdot \hat{S}) + \vec{\pi} \cdot \hat{S} \right] \\ &= \frac{\sigma_0}{2} \left[ 1 + hA + \vec{\pi}_t \cdot \hat{S} \right]\end{aligned}$$

where  $\sigma_0$  is the unpolarized cross section,  $h$  is the beam helicity (from  $-1$  to  $+1$ ),  $A$  is the electron analyzing power and  $\hat{S}$  defines the direction of quantization of the hadron spin. The quantity  $\vec{\pi}$  ( $\vec{\pi}'$ ) is a vector consisting of the helicity independent (helicity dependent) partial cross sections for each spin orientation ( $n$ ,  $t$  and  $l$ ). Finally,  $\vec{\pi}_t$  is the sum of  $\vec{\pi}$  and  $h\vec{\pi}'$ .

The various histogram weighting options in MCEEP allow examination of either  $\sigma_0$ ,  $hA$  or any of the three components of  $\vec{\pi}_t$ . Also, various single-arm cross sections can be examined. The options are summarized in Table 1. The weighting "tag" (see Table 1) can be positive or negative which will result in histograms of partial yields or cross sections respectively. For example,  $-1$  would result in a histogram of the  $(e,e'X)$  cross section vs. some kinematical variable. The cross sections are computed by dividing the appropriate yield histogram by the phase space histogram, channel by channel. Coincidence cross sections (Tag =  $-1$ ) are in  $\text{fm}^2/(\text{MeV}\cdot\text{MeV}/c\text{-sr}^2)$  for the continuum,  $\text{fm}^2/(\text{MeV}\cdot\text{sr}^2)$  for bound states and  $\text{fm}^2/\text{sr}$  for elastic scattering. Note for the continuum case the cross sections are differential in the hadron momentum, not the energy. For the singles cross sections (Tag =  $-100$ ,  $-101$ ,  $-102$ ,  $-103$ ) the units are  $\text{nb}/(\text{MeV}/c\text{-sr})$ . The polarization histograms are obtained by dividing the yield histogram for a given spin orientation by the unpolarized cross section histogram, channel by channel. (Note that, for convenience in producing normalized unpolarized cross sections and yields, MCEEP actually calculates the cross section without the factor of  $1/2$  which occurs in the above expression. Thus, all partial yields have twice the values indicated above. However, the "ratio" histograms (*i.e.*

| Tag       | Weight   |
|-----------|--|
| 0         | phase space (unit weighting)   |
| $\pm 1$   | (e,e'X)  |
| $\pm 2$   | (e,e'X) for N-type polarization (R frame)                            |
| $\pm 3$   | (e,e'X) for T-type polarization (R frame)                            |
| $\pm 4$   | (e,e'X) for L-type polarization (R frame)                            |
| $\pm 5$   | (e,e'X) for N-type polarization (S frame)                            |
| $\pm 6$   | (e,e'X) for T-type polarization (S frame)                            |
| $\pm 7$   | (e,e'X) for L-type polarization (S frame)                            |
| $\pm 8$   | (e,e'X) $h \times$ electron analyzing power                          |
| $\pm 100$ | (e,e')   |
| $\pm 101$ | (e, $\pi^-$ )  |
| $\pm 102$ | (e,p) or (e,n) (for (e,e'p) or (e,e'n) respectively)                 |
| $\pm 103$ | (e, $\pi^+$ ) or (e, $\pi^0$ ) (for (e,e'p) or (e,e'n) respectively) |

**Table 1** Histogram Weighting Options for MCEEP. Positive tags produce histograms of yields or partial yields. Negative tags produce histograms of average cross sections or polarizations. See the text for units of the cross section histograms.

the unpolarized cross section, the electron analyzing power and the recoil polarizations) are independent of this factor of 1/2 and therefore give the correct values.)

The kinematical variable for a histogram is selected by specifying an index within the array, VAR. The elements of this array are specified in the Fortran INCLUDE file "CMN\$D:VAR.CMN". The variables currently available within MCEEP along with their indices are given in the Appendix.

## 4.2 Histogram Range Determination

Since, in many cases, the user does not know ahead of time what the histogram variable ranges are, MCEEP provides defaults. The user may either specify the ranges of a given histogram within the input file or, by leaving these values blank, have the program compute them. MCEEP accomplishes this by calling the preprocessor subroutine, RANGES. RANGES uses a uniform grid over the experimental acceptance to determine the minimum and maximum values sampled for all kinematical variables. The routine which calculates these variables, KINEM, is called both in RANGES and in the main program event loop. This makes the addition of new kinematical variables simple, since the user need only add the new variable to one subroutine, KINEM.

To enhance program execution speed, RANGES may be run with a coarse grid (the default grid employs 6 iterations (from 0 to 5) in each of the six variables). However,

with a coarse grid the routine will occasionally find ranges which are significantly smaller than the actual limits. To partially compensate for this, a 10% margin is added at each end of the range. However, this may still produce a range which is too small and this will be evidenced by a large number of out-of-range events in the corresponding histograms. In this case, MCEEP can be run again with limits explicitly entered by the user or with a finer grid. In other cases RANGES may find no or only one physical solution within its coarse grid, in which case the range cannot be determined. If this happens the routine will prompt the user to type in values for the histogram limits. This obviously only makes sense if the program is run interactively.

### 4.3 Histogram Cuts

Cuts can be placed on any histogram variable. All cuts are specified within the input file. There are two options supported by the program: *global* and *histogram specific* cuts. Global cuts affect all histograms whereas histogram specific cuts affect only the histograms to which they are attached. Thus, for example, the same histogram may be examined with many different cuts in a single analysis. Note that global cuts affect even histograms with histogram specific cuts attached as well as the Transport histograms. For details regarding the format of the input, see the section on the input file.

### 4.4 Options for Displaying Histograms

There are currently three options for displaying histograms, all of which produce files suitable for the Topdrawer plotting program. The selection is made by specifying a CHARACTER\*3 name within the input file. For details regarding the format of the input, see the section on the input file.

"P1D" This option produces a regular Topdrawer histogram.

"P2D" This option produces a three-dimensional Topdrawer histogram.

"SCA" This option produces a two-dimensional Topdrawer scatter plot.

Note that since Topdrawer does not allow variable density with each point, the "SCA" option reflects only the phase space distributions and reveals nothing about the physics weighting.

It was intended that MCEEP be a self-contained program, to avoid the need for users to link to other libraries. Hence, HPLOT type histograms are not supported by MCEEP. However, the companion program TOP\_TO\_HPLOT can be used to produce HPLOT images from histogram files generated by MCEEP.

## Chapter 5

### SPECTROMETER ANALYSIS

MCEEP provides a flexible method for incorporating spectrometer/detector properties and associated uncertainties into the analysis. For each event a target Transport vector is constructed (one vector for each arm). This vector is then modified within the spectrometer analysis subroutine, SPECTROMETER, which produces an "affected" target Transport vector. In addition histograms and cuts can be made at any point along the spectrometer line. Note that, as mentioned above, the so-called "spectrometer" elements can be used to examine various non-magnetic devices as well as spectrometers.

#### 5.1 Analysis of Uncertainties

The spectrometer input section can be used to estimate the effects of various uncertainties or resolution smearing. This is accomplished by adding either fixed or gaussian distributed amounts to a given Transport ray coordinate. By comparing the results with and without this addition (in two separate runs), its effect can be evaluated. Further, these additions can be incorporated at two levels, selected by the user. The user may elect to affect the ray coordinate for the calculation of the cross section only so that the bin which the event populates does not change or he may have the addition affect only the bin but not the cross section itself. (Also, the user may elect to have both the bin and cross section affected.)

The first method of affecting only the cross section has a very important advantage. By not affecting the kinematics as far as which bins are sampled, one insures that all bins receive exactly the same statistical sample as they would if the ray coordinates were not modified. Thus, in this case, differences which result from the change in the ray coordinate reflect only physics variations and have no component due to a changing statistical sample. Using this method allows the estimation of very small uncertainties without necessitating a commensurately large number of events. In contrast, the second method would cause events to shift from bin to bin due to offsets or resolution smearing. The second method would therefore require a very large number of events so that statistical errors do not completely dominate the observed differences.

There are cases, however, where the second method of applying the offsets or resolution smearing at the level of the kinematical bins is preferable. For constrained kinematics (elastic scattering or  $(e,e'X)$  to bound states) changing one variable implies changes in other correlated variables. The cross section should not be evaluated without modifying these correlated variables as well since this would be clearly unphysical. Therefore, for these cases, it may be preferable to change the kinematics at the level of the bins rather than cross sections. In this case, the event is seen to have "pristine" kinematics from which the physics is determined. Uncertainties only affect which bin is actually populated.

## 5.2 Options

The following spectrometer analysis options are currently supported and can be selected in the input file:

- MAT** This results in multiplication of the current Transport vector by a MATrix. The matrix must be supplied by the user and must reside in the directory associated with the logical name DAT\$D. The resulting vector is then the starting point for subsequent operations or histograms or cuts. This option allows for a crude representation of the spectrometer map. Future refinements may include a more general functional form for the spectrometer transformations.
- DFT** This has the effect of performing a DriFT. It is assumed that the trajectories are straight lines and hence this option only applies to field-free regions. The exact transformations of the ray coordinates are used (rather than a first order matrix).
- ROT** This performs a "ROTation" of the Transport vector. It is assumed that the trajectories are straight lines and hence this option only applies to field-free regions. The exact transformations of the ray coordinates are used. Note that this involves tracing rays to the new (i.e. rotated) coordinate system.
- POL** Specifying this option directs the program to perform precession of the hadron POLarization through a magnetic element. The spin precession is approximated by assuming that the precession angle is a function of the net bend angle only. The bend angle is computed via a Transport matrix, so this option must be immediately followed by a "MAT" element. Precession through a series of elements can be calculated by simply stacking POL and MAT elements in pairs.
- RES** This option results in convoluting a specified Transport coordinate with a gaussian distributed RESolution function. This allows effects of resolution smearing (e.g. multiple scattering) to be simulated. This operation can be applied to either the cross sections, kinematic bins or both. By default this operation is applied to the kinematic bins only since the multiple scattering occurs after the primary scattering event and hence cannot affect the cross section. (See the section on error analysis.)
- OFF** This adds a constant OFFset (specified by the user) to a particular Transport ray coordinate. This allows evaluation of the effects of misalignments (in position sensitive detectors, for example). This operation can be applied to either the cross sections, kinematic bins or both. By default this operation is applied to the cross sections only and not the kinematic bins. This gives a more accurate representation of an actual measurement since misalignments are presumably unknown. Thus, the bin into which the event is placed should not be affected. Rather the bin is illuminated by a cross section which reflects the misalignments. (See the section on error analysis.)

- H1D** This specifies that a histogram is to be made at the current position in the spectrometer line. Any one of the six Transport coordinates can be histogrammed. The histogram is affected by all operations which precede this element in the input file.
- H2D** This specifies that a three-dimensional histogram is to be made at the current position in the spectrometer line. Any one of the six Transport coordinates can be histogrammed versus any other. The histogram is affected by all operations which precede this element in the input file.
- SCT** This specifies that a scatter plot is to be made at the current position in the spectrometer line. The histogram X and Y values are written to a file for each event. Every point in the histogram carries the same density. Thus, the resulting scatter plot does not represent the actual event population but merely reflects the phase space weighting.
- CUT** This indicates that a cut is to be placed at the current position in the spectrometer line. There are essentially four options for the cuts (see the section on the input file specification for the correct format for each).
- G or S** Selects Global or Specific cuts. Global cuts affect all histograms and scatter plots, whether they precede or follow the current element. In addition, they affect the ordinary kinematics histograms. Specific cuts affect only those Transport histograms or scatter plots to which they are explicitly attached. They cannot be attached to the kinematics histograms.
- R or E** Selects Rectangular or Elliptical cuts. Rectangular cuts refer to a single Transport coordinate. Rectangular apertures can be constructed by specifying two successive cuts on the appropriate coordinates. Elliptical cuts refer to a pair of Transport coordinates. In this case the limits for the cut refer to the semi-major/minor axes of the ellipse. For circular apertures these should be set equal to each other.

Any number and combination of the above elements can be stacked. Thus, for example one can apply a drift matrix to the scattering chamber exit window followed by multiple scattering in the exit window followed by a matrix from the exit window to the focal plane, followed by a detector misalignment, etc. The final action to be taken must give the target Transport vectors again, since it is from these objects that the physical variables,  $p_i$ , and dynamical quantities are computed. Thus, the above spectrometer elements should form a closed loop starting and ending at the target Transport vector,  $x_i^t$  and  $x_i^{t'}$  respectively:

$$q_i \rightarrow x_i^t \rightarrow x_i^{t'} \rightarrow q_i' \rightarrow p_i.$$

As indicated above, the "RES" and "OFF" options can affect either the binning variables, the cross sections or both according to the user's preference. (Defaults are provided which result in a simulation which accurately resembles the actual experiment (i.e. cross sections for "OFF" and kinematical bins for "RES").) The way in which MCEEP accomplishes this is by calling the SPECTROMETER subroutine twice. Immediately

after the first call all the cross sections (both single arm and coincidence) are computed. Only those elements which are to affect the cross sections are applied in the first call to SPECTROMETER. After the cross sections are computed, the Transport target vectors (one for each spectrometer) are reset to their original values. The SPECTROMETER subroutine is then called again and now all elements affecting the binning variables are applied. The variables for all requested Transport histograms as well as logical flags for each Transport histogram whose values depend upon whether all *specific* cuts are passed are obtained in the second call. (However, the histograms are actually incremented within the main routine, MCEEP, subsequent to the second call to SPECTROMETER.) Matrices are applied in both calls. Although this method is not the most efficient it is simpler than performing only one call and keeping two sets of variables, one for the cross sections and one for the kinematic bins.

## Chapter 6

### RUNNING MCEEP

In order to run MCEEP various logicals must be defined (VMS only) and a user input file must be set up. This along with the output generated by MCEEP is now described.

#### 6.1 Preliminaries (VMS Only)

Under VMS, the following logical names must be established before running MCEEP:

|   |        |   |
|---|--------|---|
| { | IN\$D  | Directory where input file is located               |
|   | OUT\$D | Directory where output is to be sent                |
|   | DAT\$D | Directory where various parameter files are located |

The logical DAT\$D need only be defined for certain options. In particular, if one of the built-in spectral functions is to be used or if Transport matrices are specified in the input file, this logical must point to the directory where these files are located. In addition, if the user wishes to modify the program, the logical CMN\$D must be defined so that the compiler knows where to find the various include files.

Note that under the Ultrix operating system, the directory names assumed by MCEEP are explicit.

#### 6.2 A Sample MCEEP Run

Most of the input required by MCEEP is specified via an input file (see the next section). However, MCEEP prompts the user at run-time with menus of various physics models etc. The selections are either entered interactively or they must appear in a batch command file (VMS only) (see the sample batch command file MCEEPBATCH.COM, located in SOU\$D). Note that the number of questions asked by the program depends on the input. A sample run is shown in Figure 3. The user's input is shown underlined; all other information is displayed by the program.

The possible responses to the various questions asked by MCEEP will now be summarized. See the chapter on physics models (and references quoted therein) for details on the menu options.

#### INPUT FILE

The name of the input file. MCEEP assumes the file will be located in IN\$D (for VMS) or /mceep/input/ (for Ultrix). The file extension ".inp" is assumed. The structure of the input file is described in the next section.

```

$ run mceep

Enter input file prefix (.inp) >doc
Elastic (E), Bound State (B) or Continuum (C)? b
(e,e'p) or (e,e'n)? (P/N)>p

S(p,E) X Sigma_CC1 (unpolarized) ----- 100
S(p,E) X Sigma_CC1 (polarized - Van Orden) ----- 200
Gross/Dmitrasinovic Deuterium IA ----- 300
Pion production from proton ----- 500

Enter Option>200

Deuteron: Krautschneider ----- 10
          Saha parametric fit to data ----- 11
          from EPC code ----- 12
          Bernheim data ----- 13
          Van Orden parameterization ----- 14

Enter Option or <RET> for more options>10
Compute singles X-sections? (Y/N)>n
Event number: 1000
Event number: 2000
          :
Event number: 10000
FORTRAN STOP

```

Figure 3 A sample MCEEP run. The user's input is shown underlined. Note that the number of questions asked by the program depends on the input.

### ELASTIC, BOUND STATE OR CONTINUUM

For elastic scattering (i.e.  $A(e,e'A)$ ), bound state scattering or scattering to the continuum, MCEEP will perform 2, 5 or 6 dimensional integrals respectively. If elastic scattering is chosen, MCEEP will prompt the user to select either scattering from the proton or deuteron (these are only two options currently supported). If the deuteron is chosen the user must then select one of the four available models.<sup>[3]</sup> Also, for elastic scattering in general, the user has the option of enforcing the acceptance of the hadron arm or simulating single-arm elastic scattering where the hadron kinematics are ignored. If elastic scattering is chosen, MCEEP requests no further input. For the bound state

or continuum options, MCEEP will prompt the user to choose from various models (see below and also the chapter on physics models).

(e,e'p) or (e,e'n)

This defines which form factors are to be used for certain physics options. Note that the ejectile mass is set within the input file and this option will not override the value. Finally, physics options 300 and 500 (see below) are explicitly for proton ejectiles.

### PHYSICS OPTION

MCEEP currently supports 4 physics options, numbered 100, 200, 300 and 500.

- 100 Factorized (e,e'N) calculation in PWIA. This option produces the four unpolarized response functions. If this option is selected, MCEEP will then display menus of spectral functions for various nuclei (see below).
- 200 Factorized (e,e'N) calculation in PWIA. This option produces polarization response functions as well. If no polarizations are measured and if the beam is unpolarized, this option will produce the same results as option 100. In this case option 100 is preferred since it requires less computation time. If this option is selected, MCEEP will then display menus of spectral functions for various nuclei (see below).
- 300 Relativistic (unfactorized) PWIA calculation for  $d(e,e'p)n$ . This option produces polarization observables.
- 500 Pion electroproduction in  $p(e,e'p)\pi^0$ . This option produces polarization observables as well. If this option is selected, the user will be prompted for the name of a resonance option file. The file "res\_standard.dat", located in DAT\$D (VMS) or in /mceep/dat/ (Ulrix), is provided for use with this option.

### SPECTRAL FUNCTION

If a factorized (e,e'N) option is chosen (option 100 or option 200) the user must then select from a menu of spectral distributions. The distribution chosen then multiplies the off-shell  $ep$  (or  $e\pi$ ) cross section. Additionally, the spectral function may be multiplied by an overall constant which is specified in the input file (via the variable SPEC\_FAC).

The default normalizations of each spectral function are listed in the chapter on physics models. For tabulated spectral functions, exponential interpolations (with a quadratic exponent) are performed to obtain the value for a given kinematics. For continuum scattering, a missing mass distribution function file will be requested by the program as well.

10-14 Deuteron momentum distributions.

20-23  $^3\text{He}$  momentum distributions for 2-body breakup channel. Includes a 2-dimensional spectral function,  $S(p_r, \epsilon_m)$ , to describe the continuum (i.e. 3-body breakup) channel.

30-34  $^4\text{He}$  momentum distributions for the t+p breakup channel.

40-42  $^{16}\text{O}$  PWIA momentum distributions for  $p_{1/2}$ ,  $p_{3/2}$  and  $s_{1/2}$  shells.

50-58 Harmonic oscillator momentum distributions for a variety of shells.

60-62 These options allow user-provided files to be used for spectral distributions.

## SINGLES CALCULATION

MCEEP provides for the calculation of singles cross sections and yields, if the user elects to have the program calculate them. The cross sections are currently based on the routines of Lightbody and O'Connell.<sup>[4]</sup> Answering "Y" (or "y") to this question, will cause MCEEP to call the routines which calculate these cross sections and will result in a much slower execution speed.

All of the responses required above can be put into a command file so that the program can be run in batch mode (VMS only). The command file must set up the logical names as well as include the statement: "\$ ASSIGN SYS\$COMMAND FOR005" (see the sample batch command file "mceepbatch.com").

### 6.3 Input file

The structure of the input file is now discussed. In addition, each input variable is described in detail. Finally, a sample input file is shown.

### 6.3.1 Structure

The structure of the input file follows; the variables are described in detail later. Each line below corresponds to a single line in the input file. In cases where a line exceeds the page width, it is continued on the next line with indentation. Blank lines, horizontal rules and phrases within brackets do not appear in the input file but are used here for clarity or informational purposes only.

---

#### [ITERATIONS]

N\_EVENT  
NITER1, NITER2, NITER3, NITER4, NITER5, NITER6

---

#### [MASSES]

ATARG, ZTARG, EJECT\_MASS, EM\_BOUND

---

#### [KINEMATICS]

E0, PH\_B, TH\_B, PF\_E, PH\_E, TH\_E, PF\_P, PH\_P, TH\_P

---

#### [ACCEPTANCES]

ACC\_EP, ACC\_EM, ACC\_PP, ACC\_PM  
SA\_SHAPE\_E, SA\_SHAPE\_P, DPH\_E, DTH\_E, DPH\_P, DTH\_P

---

#### [RATE PARAMETERS]

ALUM, BEAMTIME, SPEC\_FAC

---

#### [SINGLES PARAMETERS]

PFERMI, EPS, EPSD

---

#### [EXTENDED TARGETS]

TARGLEN, DRIFTE\_N, DRIFTP\_N

---

#### [BEAM PARAMETERS]

POL\_BEAM, BEAMV, BEAMD  
FWHM\_E0, FWHM\_PH\_B, FWHM\_TH\_B  
DEL\_E0, DEL\_PH\_B, DEL\_TH\_B

---

#### [SPECTROMETER ANALYSIS]

C.PID, NELMTS, THETA\_BP

[For I=1 to NELMTS:]

[OP=]"MAT", INVERT, TRNSPT\_FIL  
[ or ]

[OP=]"DFT", DRIFT\_LENGTH  
[ or ]

[OP=]"ROT", ROT\_AXIS, ROT\_ANGLE  
[ or ]

[OP=]"POL", BEND\_ANGLE  
[ or ]

[OP=]"RES", OB, NCOORDX, FWHM  
[ or ]

[OP=]"OFF", OB, NCOORDX, OFF  
[ or ]

[OP=]"H1D", IPID\_TR, TR\_MINX, TR\_MAXX, NXCHAN\_TR, NCUTS\_TR,  
[For J=1 to NCUTS\_TR:] ICUT\_IND\_TR(I,J), NCOORDX, TR\_FILE  
[ or ]

[OP=]"H2D", IPID\_TR, TR\_MINX, TR\_MAXX, TR\_MINY, TR\_MAXY,  
NXCHAN\_TR, NYCHAN\_TR, NCUTS\_TR,  
[For J=1 to NCUTS\_TR:] ICUT\_IND\_TR(I,J),  
NCOORDX, NCOORDY, TR\_FILE  
[ or ]

[OP=]"SCT", TR\_MINX, TR\_MAXX, TR\_MINY, TR\_MAXY, NCUTS\_TR,  
[For J=1 to NCUTS\_TR:] ICUT\_IND\_TR(I,J),  
NCOORDX, NCOORDY, TR\_FILE  
[ or ]

[OP=]"CUT", CUT\_DOMAIN, CUT\_TYPE,  
[for CUT\_DOMAIN = "G" and CUT\_TYPE = "R":]  
TR\_CUT\_MIN, TR\_CUT\_MAX, NCOORDX  
[for CUT\_DOMAIN = "G" and CUT\_TYPE = "E":]  
TR\_CUT\_X, TR\_CUT\_Y, NCOORDX, NCOORDY  
[for CUT\_DOMAIN = "S" and CUT\_TYPE = "R":]  
TR\_CUT\_MIN, TR\_CUT\_MAX, NCOORDX, TR\_CUT\_IND  
[for CUT\_DOMAIN = "S" and CUT\_TYPE = "E":]  
TR\_CUT\_X, TR\_CUT\_Y, NCOORDX, NCOORDY,  
TR\_CUT\_IND

C.PID, NELMTS, THETA\_BP

[For I=1 to NELMTS:]

repeat above input for the other arm

---

### [GLOBAL CUTS]

NCUTS

[For I=1 to NCUTS:]

ICUT\_VAR, CUT\_MIN, CUT\_MAX

---

[SPECIFIC CUTS]

NCUTS\_I

[For I=1 to NCUTS\_I:]

ICUT\_IND, ICUT\_VAR\_I, CUT\_MIN\_I, CUT\_MAX\_I

---

[KINEMATICS HISTOGRAMS]

NPLOTS

[For I=1 to NPLOTS:]

[PLOT\_TYPE="P1D", IPID, X\_MIN, X\_MAX, NX\_CHAN, X\_SC, X\_OFF,  
NCUTS\_PL, [For J=1 to NCUTS\_PL:] ICUT\_IND\_PL(I,J), IX\_VAR,  
PLOT\_FIL

[ or ]

[PLOT\_TYPE="P2D", IPID, X\_MIN, X\_MAX, Y\_MIN, Y\_MAX, NX\_CHAN,  
NY\_CHAN, X\_SC, Y\_SC, X\_OFF, Y\_OFF, NCUTS\_PL,

[For J=1 to NCUTS\_PL:] ICUT\_IND\_PL(I,J),  
IX\_VAR, IY\_VAR, PLOT\_FIL

[ or ]

[PLOT\_TYPE="SCA", X\_MIN, X\_MAX, Y\_MIN, Y\_MAX, X\_SC, Y\_SC,  
X\_OFF, Y\_OFF, NCUTS\_PL,

[For J=1 to NCUTS\_PL:] ICUT\_IND\_PL(I,J),  
IX\_VAR, IY\_VAR, PLOT\_FIL

---

[COMMENT LINES]

Up to 10 comment lines (read as CHARACTER\*80)

---

### 6.3.2 Variable Descriptions

Each of the variables contained within the input file is now described. They are grouped according to their order of appearance in the file which corresponds with the order given above. There is some duplication since the same variables may appear in different options under the same general category (for example, histogram limits appear in all three display options, "P1D", "P2D" and "SCA").

ITERATIONS

N\_EVENT Number of iterations (i.e. tries) for the Monte Carlo calculation.  
For a bound state case only a fraction of these will actually lead to

physical solutions within the experimental acceptance. In addition, for an elliptical aperture, the coordinates are selected to lie within the superscribed rectangle and then a test is made to guarantee that the event lies within the specified ellipse. Thus, in this case the fraction of "survivors" is approximately  $\pi/4$ .

**NITER1, ..., NITER6** The number of iterations to be used by the preprocessor routine **RANGES** in each of the six grid variables. These numbers only have relevance for the default histogram limits computed by **MCEEP**. They do not affect the statistical accuracy of the program. Since the number of grid points is given by the product of these six numbers (actually the number of points sampled =  $\prod_{i=1}^6 (N_i + 1)$  since each index starts at zero) they should be made as small as possible to enhance execution speed. **MCEEP** uses default values of 5 for any of these numbers which are left blank or set equal to zero. **NITER1** through **NITER6** correspond to **TH\_P**, **PH\_P**, **TH\_E**, **PH\_E**, **PF\_E**, **PF\_P** respectively (see below for the definition of these quantities).

### MASSES

**ATARG** The mass number of the target nucleus. For a compound target only the nucleus of interest is specified. The luminosity should reflect this as well.

**ZTARG** The atomic number of the target nucleus (relevant only for calculations of the singles cross sections).

**EJECT\_MASS** The mass of the ejectile in MeV.

**EM\_BOUND** The missing mass in MeV. If elastic scattering or the continuum case is selected this parameter is ignored. For  $p(e,e'p)\pi^0$ , for example, this parameter should be set to the mass of the  $\pi^0$ .

### KINEMATICS

**E0, PH\_B, TH\_B** The energy, in-plane and out-of-plane angles of the incident electron (units are MeV and degrees).

**PF\_E, PH\_E, TH\_E** The momentum, in-plane and out-of-plane angles of the scattered electron (units are MeV/c and degrees).

*PF\_P, PH\_P, TH\_P* The momentum, in-plane and out-of-plane angles of the ejected hadron (units are MeV/c and degrees).

### ACCEPTANCES

*ACC\_EP, ACC\_EM* The momentum acceptance of the electron arm in %. The first number corresponds to the maximum momentum and the second the minimum.

*ACC\_PP, ACC\_PM* The momentum acceptance of the hadron arm (see above).

*SA\_SHAPE\_E(P)* These are CHARACTER\*1 variables specifying the shape of the solid angle defining aperture for the electron and hadron arms respectively. For *SA\_SHAPE\_E(P)* = "R" a rectangular aperture is assumed. The angular acceptances which follow then correspond to the full length of each side of the rectangle (in mr). For *SA\_SHAPE\_E(P)* = "E" an elliptical aperture is assumed. The angular acceptances then correspond to the lengths of each side of a superscribed rectangle (*i.e.* twice the semi-major and semi-minor axes of the ellipse).

*DPH\_E, DTH\_E* The in-plane and out-of-plane angular acceptance of the electron arm in milliradians (see above).

*DPH\_P, DTH\_P* The in-plane and out-of-plane angular acceptance of the hadron arm in milliradians (see above).

### RATE PARAMETERS

*ALUM* Luminosity in  $\mu\text{A}\cdot\text{g}/\text{cm}^2$ . This number must take into account isotopic abundance as well as the orientation of the target relative to the beam (for solid targets).

*BEAMTIME* The total beamtime in hours. This will affect the overall magnitude of the yield histograms but has no effect on the Monte Carlo statistics. *BEAMTIME* only enters into the normalization in generating yields from the computed cross sections. The statistical accuracy of the Monte Carlo calculation is affected only by *N\_EVENT*.

*SPEC\_FAC* The spectroscopic factor for the  $(e,e'N)$  process. This number multiplies the  $(e,e'N)$  spectral function when one is chosen from the menu.

## SINGLES PARAMETERS

*PFERMI* The Fermi momentum (relevant only for calculations of the singles cross sections).

*EPS* The nucleon separation energy in MeV (relevant only for calculations of the singles cross sections).

*EPSD* The  $\Delta$  separation energy in MeV (relevant only for calculations of the singles cross sections).

## EXTENDED TARGETS

*TARGLEN* Total target length in cm. Thus, the target extension is taken to be  $\pm$  half this value. For a point target this value should be set to zero.

*DRIFTE\_N* This is the nominal drift in meters to the solid angle defining aperture for the electron arm. "Nominal" refers to the distance between the nominal beam-target interaction point and the center of the aperture. This only has relevance for extended targets.

*DRIFTP\_N* This is the nominal drift in meters to the solid angle defining aperture for the hadron arm. This only has relevance for extended targets.

## BEAM PARAMETERS

*POL\_BEAM* The polarization of the beam (from  $-1$  to  $+1$ ). For an unpolarized beam this parameter should be set to zero.

*BEAMV* For a dispersed beam this specifies the vertical extent of the beam at the nominal target position in  $\pm$  mm. If the beam is bent so that it makes an angle  $\theta_b$  with respect to the laboratory floor (e.g. by using a beam swinger to go out-of-plane) the vertical extent at the target will be  $BEAMV/\cos \theta_b$ . Division by  $\cos \theta_b$  is done automatically by the program so that the input parameter, *BEAMV*, should not reflect the out-of-plane beam. For an achromatic beam this parameter should be set to zero.

*BEAMD* For a dispersed beam this gives the momentum spread in  $\pm\%$ . The momentum and vertical extent of the beam are assumed to be related

linearly. For an achromatic beam this parameter should be set to zero.

**FWHM\_E0** The full width at half maximum (in % of E0) of a gaussian distributed addition to the beam energy. This can be used to estimate the effects of a finite spread in beam energy. For a monochromatic beam this value should be set to zero.

**FWHM\_PH\_B** The FWHM (in mr) of a gaussian distributed addition to the beam in-plane angle. This can be used to estimate the effect of multiple scattering in the scattering chamber entrance window or target for example.

**FWHM\_TH\_B** The FWHM (in mr) of a gaussian distributed addition to the beam out-of-plane angle.

**DEL\_E0** An offset (in % of E0) to be added to the beam energy. This can be used to estimate the effect of inaccurate knowledge of the centroid beam energy.

**DEL\_PH\_B** An offset (in mr) to be added to the beam in-plane angle.

**DEL\_TH\_B** An offset (in mr) to be added to the beam out-of-plane angle.

## SPECTROMETER ANALYSIS

**C\_PID,NELMTS** C\_PID is a CHARACTER\*1 variable which identifies one of the two coincidence spectrometers. Thus, this variable can take two values, "E" or "P", depending on whether the electron arm or hadron (proton) arm spectrometer elements follow. NELMTS specifies the number of entries associated with the specification of the spectrometer and associated offsets, etc. If one does not wish to incorporate the spectrometers into the analysis this line should be either "E,0" or "P,0". Note, however, that the spectrometer bend-plane angle, THETA\_BP (see below), must be included if one wishes to examine recoil polarization variables in the spectrometer frame.

**THETA\_BP** If the spectrometer is to be incorporated the variable THETA\_BP must be set properly. This variable defines the orientation of the spectrometer bend plane (in degrees). The following examples illustrate the convention used.

-90 Bends vertically upward

+90 Bends vertically downward

180 Bends leftward

0 Bends rightward

Here, left and right refer to the bending direction as one looks down the optic axis from the target.

*OP* A CHARACTER\*3 variable which specifies the type of Operation to be performed for a given transformation element. Currently, ten options are supported. The input for each element depends on the type of operation specified.

*MAT* Multiplication of the current Transport vector by a matrix. The matrix must be supplied by the user and must reside in the directory assigned to the logical name DAT\$D.

*DFT* Perform a drift through a field-free region.

*ROT* Refer the Transport ray coordinates to a rotated system. This only works for field-free regions.

*POL* Precess the hadron spin through a magnetic element.

*RES* Addition of a gaussian distributed function to a particular Transport ray coordinate.

*OFF* Addition of a constant offset to a particular Transport ray coordinate.

*H1D* A histogram of a Transport coordinate.

*H2D* A three-dimensional histogram of Transport coordinates.

*SCT* A scatter plot of Transport coordinates.

*CUT* A cut on a particular Transport coordinate or pair of coordinates (see below).

OP = MAT

*INVERT* A LOGICAL\*1 variable ("T" or "F") which indicates whether or not the Transport matrix supplied by the user should first be inverted before its application to the current Transport vector.

**TRNSPT\_FIL** The name of the file which contains the user's Transport matrix. This file must be located in the directory associated with the logical name DAT\$D.

OP = DFT

**DRIFT\_LENGTH** The drift distance in cm.

OP = ROT

**ROT\_AXIS** Rotation axis ("X", "Y" or "Z") refers to rotations about one of the three Transport axes.

**ROT\_ANGLE** Angle of rotation in degrees. Positive angles imply passive (i.e. coordinate system) rotations with a sense given by the right hand rule (e.g. for an "X" rotation, the Y axis is rotated into the direction of the original Z axis).

OP = POL

**BEND\_ANGLE** The bend angle for the magnetic element. (This angle should normally be zero for a quadrupole magnet.) Note that the POL option calculates spin precession from the bend angle for a given ray. Thus, the POL element must be followed by a MAT element from which the bend angle is determined.

OP = RES

**OB A CHARACTER\*1** variable which specifies the "object" affected by the above operation. Here, object is either "K", "S", "B" or "D" (see the text for a complete description of these options):

**OB = "K"** The operation affects the Kinematics only. Thus, the cross section is computed from the "unperturbed" values and only the binning intervals for histograms are affected.

**OB = "S"** The operation affects the cross section (Sigma) only leaving the binning variables undisturbed.

**OB = "B"** The operation affects Both the kinematics and cross sections.

**OB = "D"** Default selection. For OP = "RES" this is the same as OB = "K". (This makes sense when OP = "RES" is used to estimate the effects of multiple scattering. In this case the measured kinematics are affected but the cross sections are

unchanged since the primary scattering event occurred before the multiple scattering.) However, for  $OP = "OFF"$  this is the same as  $OB = "S"$ . (This is sensible when  $OP = "OFF"$  is used to estimate the effects of a misplaced spectrometer or spectrometer element or detector. In this case since this misplacement is presumably unknown, the kinematics are not affected but a given bin effectively corresponds to a different cross section. This would then correspond to what is actually measured.) See the section on error analysis for further comments.

**NCOORDX** The index of the Transport coordinate to be affected. This value should be 1,2,...,6 for  $x, \theta, y, \phi, l$  or  $\delta$  respectively.

**FWHM** FWHM for gaussian distributed addition to a particular Transport coordinate. Units are in the standard Transport convention (cm, mr or %).

#### OP = OFF

**OB** A CHARACTER\*1 variable which specifies the "object" affected by the above operation. See above (under  $OP = "RES"$ ) for details.

**NCOORDX** The index of the Transport coordinate to be affected. See above for details.

**OFF** Offset to a particular Transport coordinate. Units are in the standard Transport convention (cm, mr or %).

#### OP = H1D

**IPID.TR** Specifies weighting option for the histogram. See the text for a complete description of the various options.

**TR\_MINX, TR\_MAXX** Lower and upper limits for the histogram in standard Transport units.

**NXCHAN.TR** Number of bins for the histogram.

**NCUTS.TR** Number of Transport cuts to apply to this histogram.

**ICUT\_IND.TR** Indices of the cuts (NCUTS\_TR values).

**NCOORDX** Index specifying which Transport coordinate is to be histogrammed. This value should be 1,2,...,6 for  $x, \theta, y, \phi, l$  or  $\delta$  respectively.

*TR\_FILE* Name of the file which will contain the histogram. The file will be located in the directory associated with the logical name OUT\$D.

OP = H2D

*IPID\_TR* Specifies weighting option for the histogram.

*TR\_MINX, TR\_MAXX* Lower and upper limits for the X histogram variable in standard Transport units.

*TR\_MINY, TR\_MAXY* Lower and upper limits for the Y histogram variable in standard Transport units.

*NXCHAN\_TR* Number of X bins for the histogram.

*NYCHAN\_TR* Number of Y bins for the histogram.

*NCUTS\_TR* Number of Transport cuts to apply to this histogram.

*ICUT\_IND\_TR* Indices of the cuts (*NCUTS\_TR* values).

*NCOORDX, NCOORDY* Indices specifying the X and Y Transport coordinates to be histogrammed. This value should be 1,2,...,6 for  $x, \theta, y, \phi, l$  or  $\delta$  respectively.

*NCOORDY* The index specifying the Y Transport coordinate to be histogrammed.

*TR\_FILE* Name of the file which will contain the histogram. The file will be located in the directory associated with the logical name OUT\$D.

OP = SCT

*TR\_MINX, TR\_MAXX* Lower and upper limits for the X scatter plot variable in standard Transport units.

*TR\_MINY, TR\_MAXY* Lower and upper limits for the Y scatter plot variable in standard Transport units.

*NCUTS\_TR* Number of Transport cuts to apply to this scatter plot.

*ICUT\_IND\_TR* Indices of the cuts (*NCUTS\_TR* values).

*NCOORDX, NCOORDY* Indices specifying the X and Y Transport coordinates for the scatter plot. This value should be 1,2,...,6 for  $x, \theta, y, \phi, l$  or  $\delta$  respectively.

*TR\_FILE* Name of the file which will contain the scatter plot. The file will be located in the directory associated with the logical name OUT\$D.

## OP = CUT

*CUT.DOMAIN* CHARACTER\*1 variable specifying whether the cut is Globally applied to all histograms (including non-Transport histograms) or applies to a Specific Transport histogram.

*CUT.TYPE* CHARACTER\*1 variable specifying whether the cut is Rectangular or Elliptical.

[For *CUT.DOMAIN* = "G" and *CUT.TYPE* = "R"]

*TR.CUT.MIN* The minimum value for the cut in standard Transport units.

*TR.CUT.MAX* The maximum value for the cut in standard Transport units.

*NCOORDX* Index specifying the Transport coordinate for the cut.

[For *CUT.DOMAIN* = "G" and *CUT.TYPE* = "E"]

*TR.CUT.X*, *TR.CUT.Y* The length of the semi-major/minor axes for the X and Y coordinates for the cut.

*NCOORDX*, *NCOORDY* Indices specifying the X and Y Transport coordinates for the cut.

[For *CUT.DOMAIN* = "S" and *CUT.TYPE* = "R"]

*TR.CUT.MIN* The minimum value for the cut in standard Transport units.

*TR.CUT.MAX* The maximum value for the cut in standard Transport units.

*NCOORDX* Index specifying the Transport coordinate for the cut.

*TR.CUT.IND* Unique index labeling this cut.

[For *CUT.DOMAIN* = "S" and *CUT.TYPE* = "E"]

*TR.CUT.X*, *TR.CUT.Y* The length of the semi-major/minor axes for the X and Y coordinates for the cut.

*NCOORDX*, *NCOORDY* Indices specifying the X and Y Transport coordinates for the cut.

*TR.CUT.IND* Unique index labeling this cut.

## GLOBAL CUTS

*NCUTS* The number of global cuts to be applied to all histograms.

*ICUT.VAR* The index for the variable to be cut.

*CUT.MIN* The minimum value for the cut.

*CUT.MAX* The maximum value for the cut.

### SPECIFIC CUTS

*NCUTS.I* The number of histogram specific cuts. These cuts affect only the histograms to which they are attached.

*ICUT.IND* An identifier referring to a particular cut. This tag is specified in attaching the cut to a particular histogram.

*ICUT.VAR.I* The index for the variable to be cut.

*CUT.MIN.I* The minimum value for the cut.

*CUT.MAX.I* The maximum value for the cut.

### KINEMATICS HISTOGRAMS

*NPLOTS* The number of histograms to be generated.

*PLOT.TYPE* A CHARACTER\*3 variable denoting the type of plot file to be generated. Options are:

*PLOT.TYPE* = "P1D" Topdrawer histogram.

*PLOT.TYPE* = "P2D" Three-dimensional Topdrawer histogram.

*PLOT.TYPE* = "SCA" Topdrawer scatter plot.

For *PLOT.TYPE* = P1D

*IPID* Index specifying weighting factor for histogram (i.e. the dependent variable). Various options include (as described in detail in the text) phase space volumes, (e,e'p) yield or average cross section, partial yields for recoil polarization components or average polarizations as well as various singles yields and average cross sections.

*X.MIN, X.MAX* Minimum and maximum values for independent variable (if left blank, the program will compute them).

*NX.CHAN* Number of bins for histogram.

*X.SC* Scale factor for histogram. The default units for histograms are MeV for energies and radians for angles.

*X.OFF* Offset for histogram. Note that if a histogram is scaled, the offsets reflect the rescaling. Thus, for example, if a histogram is scaled by  $180/\pi$  to convert from radians to degrees, the offset is interpreted as degrees.

*NCUTS.PL* Number of histogram specific cuts to be applied to the histogram.

*ICUT.IND.PL(I,J)* The tag specifying the cut to be applied to the histogram for  $J=1$  to *NCUTS.PL*.

*IX.VAR* Index specifying kinematic variable for histogram (independent variable).

*PLOT.FIL* Filename for the histogram. All histograms will be located in the directory associated with the logical name *OUT\$D*.

For *PLOT.TYPE = P2D*

*IPID* Index specifying weighting factor for histogram (i.e. the dependent variable).

*X.MIN, X.MAX* Minimum and maximum values for X variable (if left blank, the program will compute them).

*Y.MIN, Y.MAX* Minimum and maximum values for Y variable (if left blank, the program will compute them).

*NX.CHAN, NY.CHAN* Number of X and Y bins for histogram.

*X.SC, Y.SC* Scale factors for X and Y variables. The default units for histograms are MeV for energies and radians for angles.

*X.OFF, Y.OFF* Offsets for X and Y variables.

*NCUTS.PL* Number of histogram specific cuts to be applied to the histogram.

*ICUT.IND.PL(I,J)* The tag specifying the cut to be applied to the histogram for  $J=1$  to *NCUTS.PL*.

*IX.VAR, IY.VAR* Indices specifying X and Y kinematic variables for histogram (independent variables).

*PLOT.FIL* Filename for the histogram. All histograms will be located in the directory associated with the logical name *OUT\$D*.

For PLOT\_TYPE = SCA

*X\_MIN, X\_MAX* Minimum and maximum values for X variable (if left blank, the program will compute them).

*Y\_MIN, Y\_MAX* Minimum and maximum values for Y variable (if left blank, the program will compute them).

*X\_SC, Y\_SC* Scale factors for X and Y variables. The default units are MeV for energies and radians for angles.

*X\_OFF, Y\_OFF* Offsets for X and Y variables.

*NCUTS\_PL* Number of histogram specific cuts to be applied to the histogram.

*ICUT\_IND\_PL(I,J)* The tag specifying the cut to be applied to the histogram for  $J=1$  to *NCUTS\_PL*.

*IX\_VAR, IY\_VAR* Indices specifying X and Y kinematic variables (independent variables).

*PLOT\_FIL* Filename for the scatter plot. All scatter plots will be located in the directory associated with the logical name **OUTSD**.

**COMMENT LINES**

*COMMENT(I)* Any number of comment lines can appear at the end of the file. The first 10 lines will be written to the summary file.

### 6.3.3 Sample Input File

A sample input file for MCEEP is shown in Figure 4. The case is for  $d(e,e'p)$  at  $\bar{q} = 1$  GeV/c and  $\bar{p}_r = 0$ . The acceptances and drift distances correspond to the nominal values for the CEBAF Hall A high resolution spectrometers (HRS). The sample file does not include any beam smearing or offsets (these values are all set to 0). The electron spectrometer analysis includes a first order Transport matrix from the target to the focal plane (for the "nominal" HRS tune) followed by an offset in  $x$  and a rectangular aperture in  $x$  and  $y$  at the focal plane. (This aperture may select only those events which lie within the focal plane wire chambers for instance, although currently no rotation into the focal plane is performed). In addition, various Transport histograms are examined, one of which corresponds to  $\phi$  at the target with the restriction that the event also lies within the rectangular aperture described above. No spectrometer analysis is being performed for the hadron arm as indicated by the presence of the "P,0,-90." line. (Note, however, that the "-90." must be included to establish a vertically bending spectrometer since various

spectrometer-frame polarization observables are being histogrammed.) In addition to the Transport histograms, several kinematics histograms are also requested, some of which have cuts attached. Note that the global cuts specified before the kinematics histograms apply to all histograms, even the Transport histograms. Finally, two comment lines are typed both of which will appear in the output summary file.

```

Iterations { 10000
            { 5, 5, 5, 5, 5, 5
Masses     { 2., 1., 938.2796, 2.2
Kinematics { 1653., 0., 0., 1218., 37.0, 0., 1000., -47.1, 0.
Acceptances { 5.0, -5.0, 5.0, -5.0
             { E, E, 60., 130., 60., 130.
Rate Parameters { 0.810, 1., 1.
Singles Parameters { 45., 2.2, 2.2
Extended Targets { 5., 1.65, 1.65
Beam Parameters { 0.4, 0., 0.
                { 0., 0., 0.
                { 0., 0., 0.
Spectrometer Analysis { E, 8, -90.
                     { H1D, 1, -40., 40., 80, 2, 1, 2, 4, yield_trphe.top
                     { MAT, F, trpt_hrs.dat
                     { OFF, D, 1, 1.
                     { CUT, S, R, -60., 60., 1, 1
                     { CUT, S, R, -20., 20., 3, 2
                     { SCT, -100., 100., -50., 50., 0, 1, 3, phsp_trxye.top
                     { H2D, 1, -100., 100., -50., 50., 20, 20, 0, 1, 3, yield_trxye.top
                     { MAT, T, trpt_hrs.dat
                     { P, 0, -90.
Global Cuts { 1
            { 26, 0., 60.
Specific Cuts { 2
              { 1, 15, 410., 460.
              { 2, 16, 975., 1025.
Kinematics Histograms { 10
                     { P1D, 0, , , 50, 1., 0., 0, 26, phsp_pr.top
                     { P1D, 1, , , 50, 1., 0., 0, 26, yield_pr.top
                     { P1D, -1, , , 50, 1., 0., 0, 26, sig_pr.top
                     { P1D, -1, , , 50, 1., 0., 2, 1, 2, 26, sig_pr.c.top
                     { P2D, 1, , , , 25, 25, 1., 1., 0., 0., 0, 15, 16, yield_wq.top
                     { SCA, , , , , 1., 1., 0., 0., 0, 15, 16, phsp_wq.top
                     { P1D, 6, , , 50, 1., 0., 0, 12, tpoly_pf.top
                     { P1D, -6, , , 50, 1., 0., 0, 12, tpol_pf.top
                     { P1D, 7, , , 50, 1., 0., 0, 12, lpoly_pf.top
                     { P1D, -7, , , 50, 1., 0., 0, 12, lpol_pf.top
Comment Lines { This is a comment line.
              { This is another comment line.

```

Figure 4 Sample Input File for MCEEP (IN\$D:DOC.INP).

## Chapter 7

### PHYSICS MODELS OF MCEEP

Currently, MCEEP provides a menu of several basic physics models devoted mainly to gross descriptions of (e,e'N) reactions. It is hoped that as the need arises, users of the program will incorporate their own models of these and other reactions. Effort has been made to allow inclusion of new and hopefully more sophisticated models with ease. The next chapter describes the steps needed to add a new physics model. This chapter is devoted to a description of the models MCEEP currently employs.

#### 7.1 General Formalism of (e,e'N)

A detailed analysis of the (e,e'N) reaction has been developed by Picklesimer and Van Orden.<sup>[5]</sup> Their analysis shows that there are 18 independent response functions in the general case, for a polarized electron beam, involving nucleon polarization and non-coplanar kinematics:

$$\begin{aligned} \frac{d^3\sigma}{d\omega d\Omega_e d\Omega_p} = & \frac{m|\vec{p}'|}{2(2\pi)^3} \left[ \frac{d\sigma}{d\Omega_e} \right]_{Mott} \times \{ v_L(R_L + R_L^n S_n) + v_T(R_T + R_T^n S_n) \\ & + v_{TT} [(R_{TT} + R_{TT}^n S_n) \cos 2\phi_z + (R_{TT}^l S_l + R_{TT}^t S_t) \sin 2\phi_z] \\ & + v_{LT} [(R_{LT} + R_{LT}^n S_n) \cos \phi_z + (R_{LT}^l S_l + R_{LT}^t S_t) \sin \phi_z] \\ & + hv_{LT'} [(R_{LT'} + R_{LT'}^n S_n) \sin \phi_z + (R_{LT'}^l S_l + R_{LT'}^t S_t) \cos \phi_z] \\ & + hv_{TT'} (R_{TT'}^l S_l + R_{TT'}^t S_t) \}. \end{aligned}$$

The response functions,  $R$ , depend on  $\vec{q}$ ,  $\omega$ ,  $T_p$  (the proton kinetic energy) and  $\theta_{pq}$  (the nucleon emission angle with respect to  $\vec{q}$ ). Here,  $\phi_z$  is the angle between the electron scattering plane and the plane containing  $\vec{q}$  and the detected nucleon. The  $v$ 's are known kinematic factors weighting the various virtual photon polarization states and  $[d\sigma/d\Omega_e]_{Mott}$  is the cross section for scattering from a structureless Dirac particle. The  $S$ 's are the three components of a unit vector pointing along the nucleon spin direction.

The response functions arise from products of various components of the nuclear current and are therefore expected to exhibit varying sensitivities to different aspects of the reaction. Measurements involving separation of these response functions will consequently provide selectivity to various dynamical models of the (e,e'N) reaction. Conversely, under certain assumptions, these response functions can be calculated and the results used to simulate gross features of (e,e'N) experiments. In the following section, the form of the (e,e'N) cross section in the simplest nontrivial calculation is given.

## 7.2 (e,e'N) in PWIA (Options 100 and 200)

MCEEP's menu option numbers 100 and 200 provide for evaluation of the coincidence (e,e'N) cross section in PWIA (Plane Wave Impulse Approximation). Under option 100, MCEEP computes only the four unpolarized response functions. Option 200 provides calculations for all response functions which are not zero in PWIA. Both options produce the same results for the unpolarized cross section. The information provided by option 200 is therefore a superset of that for option 100. However, if only unpolarized observables are desired, option 100 is preferred since it requires less computation time.

### 7.2.1 Factorization of the Cross Section

In PWIA a simple form for the (e,e'N) cross section arises. In this approximation the cross section factors into an elementary electron-nucleon off-shell cross section times a quantity which contains the nuclear structure information, the spectral function:<sup>[6]</sup>

$$\sigma_{eeN} = K \sigma_{eN} \frac{1}{\eta} \alpha_{sf} S(\vec{p}_r, \epsilon_m)$$

where  $K$  is a kinematical factor. The recoil factor,  $\eta$ , is taken as unity for scattering to the continuum of the residual system and for scattering to a bound state it is given by

$$\eta = 1 - \frac{E_p \vec{p}_p \cdot \vec{p}_r}{E_r |\vec{p}_p|^2}$$

where  $E_{p(r)}$  is the total energy of the detected nucleon (recoiling system) and  $\vec{p}_p$  is the nucleon final momentum. The spectral function,  $S$ , represents the joint probability for finding within the nucleus a nucleon of momentum  $-\vec{p}_r$  and separation energy  $\epsilon_m$ . The spectral function calculated by MCEEP also contains the overall multiplicative (spectroscopic) factor,  $\alpha_{sf}$ . This factor is specified in the user input file. All of the dependence on virtual photon polarization is contained within the  $eN$  cross section. Many ambiguities exist in the extrapolation of the on-shell cross section to that for a bound nucleon. However, all prescriptions are fairly consistent for nucleons which are nearly on-shell. MCEEP uses the "CC1" prescription of de Forest for  $\sigma_{eN}$ .<sup>[7]</sup> MCEEP provides a variety of nuclear spectral functions; the various choices are described in the next subsection. In most cases the spectral function itself is assumed to factorize:

$$S(\vec{p}_r, \epsilon_m) = |\phi(\vec{p}_r)|^2 f(\epsilon_m).$$

For a bound state the missing mass distribution function,  $f(\epsilon_m)$ , is a delta function. In this case the missing mass integral leads to the Jacobian given above ( $\eta$ ) and the cross section becomes 5-fold differential instead of 6-fold. Because of the difference in dimensionality (i.e. the effective constraint implied by the fixed missing mass for the bound state case), MCEEP treats the bound state problem and the continuum problem separately. For the continuum case the missing mass distribution function must be supplied to MCEEP via a file (see the next subsection).

## 7.2.2 Spectral Functions

MCEEP provides a variety of spectral functions to use with the factorized models for the  $(e,e'N)$  reaction. The various options are described below. The deuteron,  $^3\text{He}$  and  $^4\text{He}$  momentum distributions are displayed in Figures 5, 6 and 7 respectively. The integrals of each momentum distribution used by MCEEP are shown in Table 2.

Note that if the user selects the continuum case and a spectral function option which only specifies the  $p_r$  dependence, a missing mass distribution file will also be requested by the program.

### Deuteron

- 10: This parameterization is due to Krautschneider.<sup>[8]</sup> The integral is forced to one in the MCEEP implementation.
- 11: This is a parametric fit to the data of Bernheim (see option 13) by A. Saha.<sup>[9]</sup>
- 12: This parameterization is used by the program EPC of Lightbody and O'Connell<sup>[4]</sup>, the routines of which are currently used in MCEEP to generate singles cross sections.
- 13: Experimental distribution measured by Bernheim *et al.*<sup>[10]</sup>
- 14: A parameterization by J.W. Van Orden.<sup>[11]</sup>

### $^3\text{He}$

- 20: This is the distribution of Meier-Hajduk *et al.*<sup>[12]</sup> If the continuum case is selected the 3-body breakup part of the distribution is used, otherwise the 2-body breakup distribution is used.
- 21: This parameterization is from a variational calculation using the Argonne potential for the 2-body breakup of  $^3\text{He}$ .<sup>[13]</sup>
- 22: This parameterization is from a variational calculation using the Urbana potential for the 2-body breakup of  $^3\text{He}$ .<sup>[13]</sup>
- 23: This is an experimental distribution from Jans *et al.*<sup>[14]</sup> and Marchand *et al.*<sup>[15]</sup> These data are for the 2-body break-up channel only. Also, the data for  $p_r=155-195$  MeV/c are averages of the Kinematics I and Kinematics II data sets.

# Deuteron

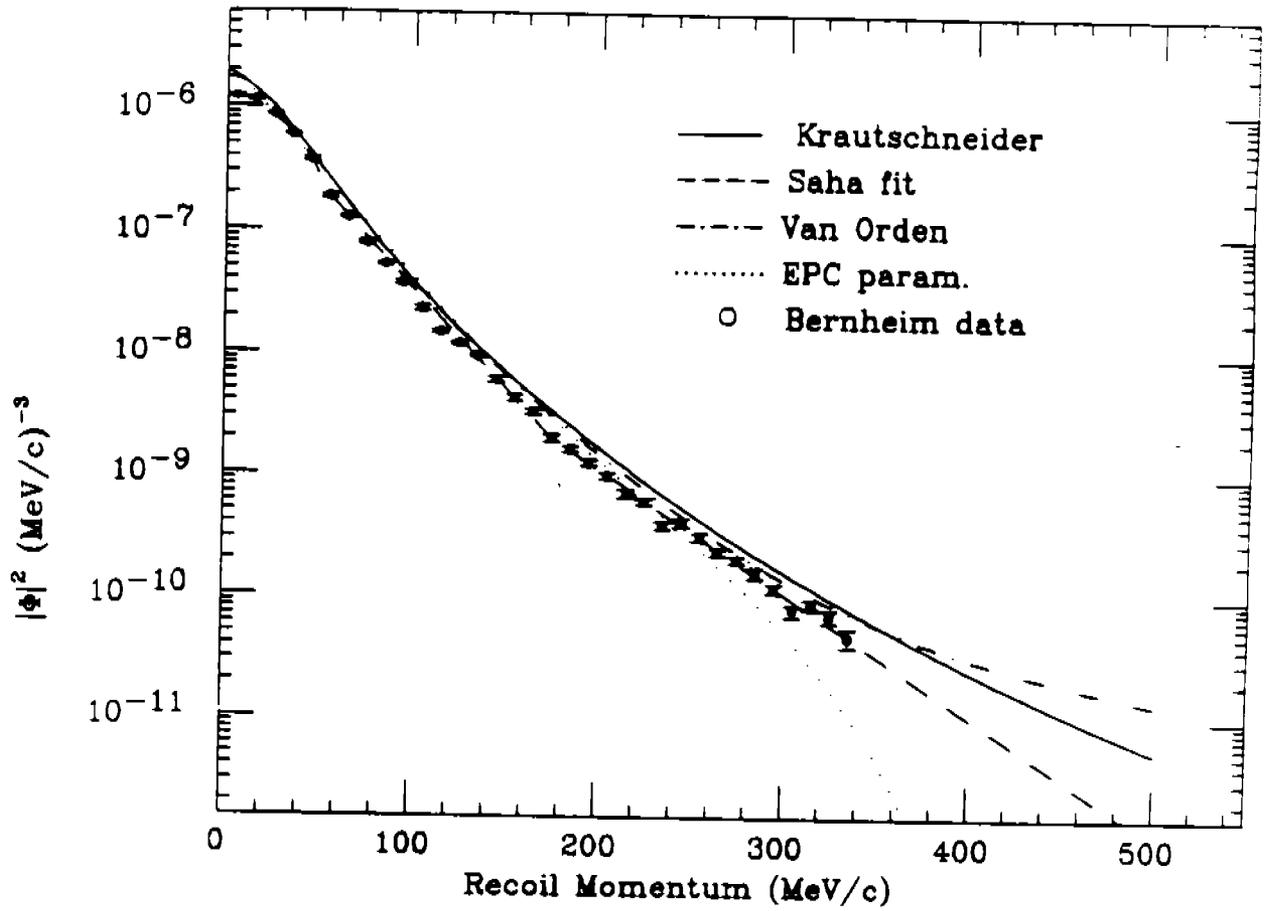
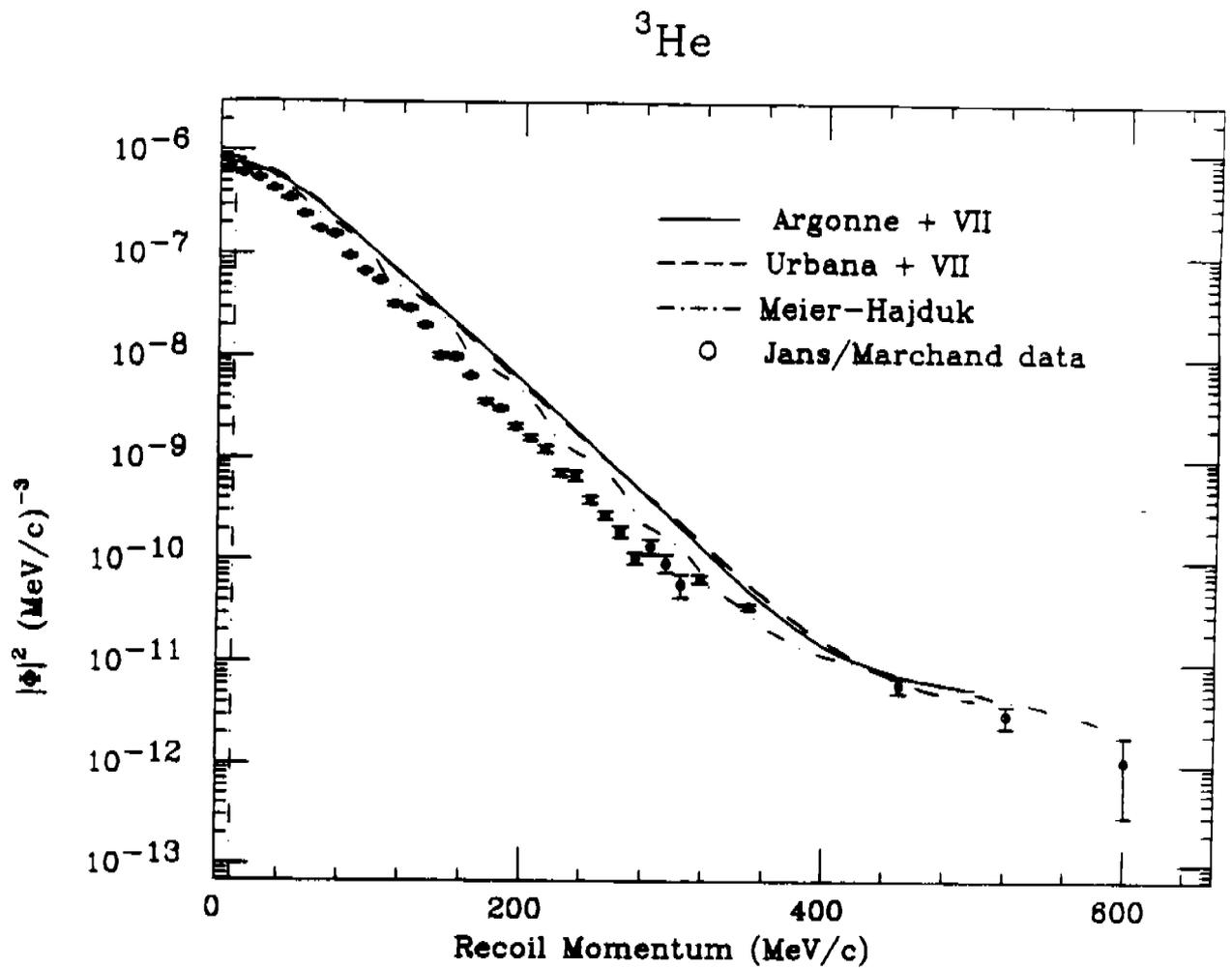


Figure 5. Momentum distributions employed by MCEEP for  $d(e,e'p)n$ . See the text for details regarding the various distributions.



**Figure 6.** Momentum distributions employed by MCEEP for the two-body breakup channel of  ${}^3\text{He}$  (i.e.  ${}^3\text{He}(e,e'p)d$ ). See the text for details regarding the various distributions.

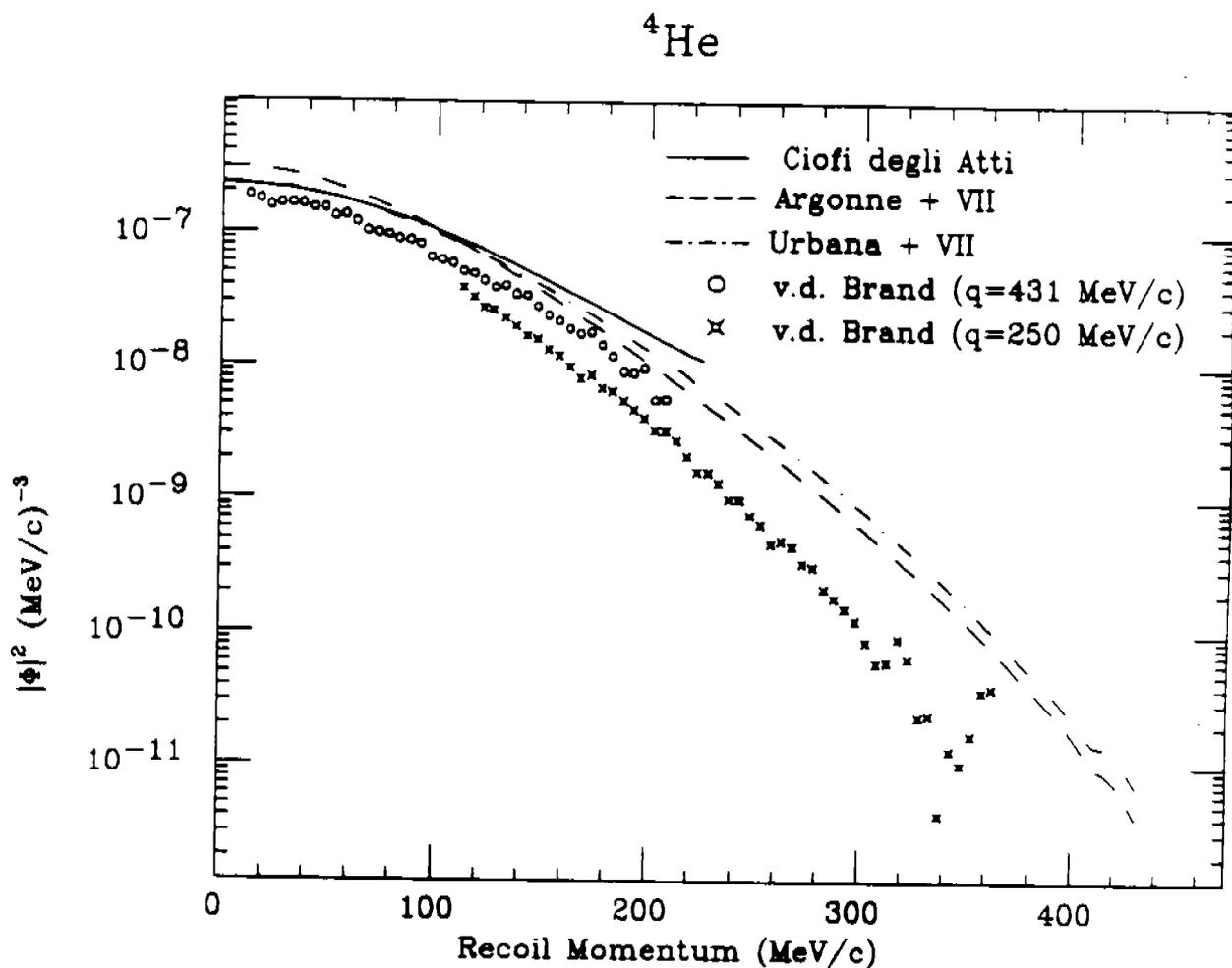


Figure 7. Momentum distributions employed by MCEEP for the two-body breakup channel of  ${}^4\text{He}$  (i.e.  ${}^4\text{He}(e,e'p)t$ ). See the text for details regarding the various distributions.

| Option #    | Integration Range<br>(MeV/c) | Integral      |
|-------------|------------------------------|---------------|
| 10          | 0 to $\infty$                | 1             |
| 11          | 0 to $\infty$                | 0.810         |
| 12          | 0 to $\infty$                | 0.936         |
| 13          | 0 to $\infty$                | 0.776         |
| 14          | 0 to $\infty$                | 1             |
| 20 (2-body) | 0 to $\infty$                | 1.62          |
| 21          | 0 to 500                     | 2             |
| 22          | 0 to 500                     | 2             |
| 23          | 0 to $\infty$                | 1.07          |
| 30          | 0 to 225                     | 2             |
| 31          | 0 to 430                     | 1.92          |
| 32          | 0 to 430                     | 2             |
| 33          | 0 to 207.5                   | 1.139         |
| 34          | 112.5 (0) to 362.5           | 0.405 (0.998) |
| 40          | 0 to $\infty$                | 2             |
| 41          | 0 to $\infty$                | 4             |
| 42          | 0 to $\infty$                | 2             |
| 50-58       | 0 to $\infty$                | 1             |

**Table 2** Integrals for MCEEP momentum distributions:  $4\pi \int dp_r p_r^2 |\phi(p_r)|^2$ . Note that in some cases the experimental distribution is extrapolated to yield the integral shown.

${}^4\text{He}$

- 30: This is a parameterization from Ciofi degli Atti.<sup>[16]</sup> Note that for  $p_r > 225$  MeV/c this parameterization yields unphysical results. Therefore, the momentum distribution is set to zero above this value.
- 31: This parameterization is for the t+p breakup channel of  ${}^4\text{He}$  using the Argonne potential.<sup>[13]</sup> The parameterization becomes unreasonable for  $p_r > 430$  MeV/c and so the momentum distribution is set to zero in this range.
- 32: This parameterization is for the t+p breakup channel of  ${}^4\text{He}$  using the Urbana

potential.<sup>[13]</sup> The parameterization becomes unreasonable for  $p_r > 430$  MeV/c and so the momentum distribution is set to zero in this range.

- 33: This is the experimental momentum distribution from van den Brand *et al.*<sup>[17]</sup> for the t+p breakup channel of  $^4\text{He}$  measured at  $\bar{q} = 431$  MeV/c. Note that this data set extends only to  $p_r = 207.5$  MeV/c. Therefore, the momentum distribution is set to zero above this value.
- 34: This is the experimental momentum distribution from van den Brand *et al.*<sup>[17]</sup> for the t+p breakup channel of  $^4\text{He}$  measured at  $\bar{q} = 250$  MeV/c. Note that this data set extends from  $p_r = 112.5$  to  $362.5$  MeV/c. Extrapolations give fairly reasonable values for  $p_r < 112.5$  MeV/c (within a factor of two of the  $\bar{q} = 431$  MeV/c data set). However, extrapolation beyond  $362.5$  MeV/c yields unreasonable values. Therefore, the momentum distribution is set to zero above this range.

$^{16}\text{O}$

MCEEP currently employs the parameterization of J.W. Van Orden for the momentum distributions of  $^{16}\text{O}$ .<sup>[11]</sup> Options 40, 41 and 42 correspond to the  $1p_{1/2}$ ,  $1p_{3/2}$  and  $1s_{1/2}$  shells respectively.

#### Harmonic Oscillator

MCEEP provides a set of generic harmonic oscillator momentum distributions. If one of these is selected the user must also enter the oscillator parameter (in fm). Options 50-58 correspond respectively to the 1s, 1p, 2s, 1d, 2p, 1f, 3s, 2d and 1g shells.

#### External Files

These options allow the use of externally supplied spectral distributions. The distribution must be represented by an array (contained in a file) on which MCEEP can interpolate. The exact format required is specified in the file "spectral.for".

- 60: Two-dimensional spectral function  $S(p_r, \epsilon_m)$ .
- 61: Momentum distribution  $|\phi(p_r)|^2$  for a bound state.
- 62: Momentum distribution and missing mass distribution,  $f(\epsilon_m)$ , for the continuum case.

### 7.3 Relativistic $d(e,e'p)n$ (Option 300)

MCEEP provides a fully relativistic calculation for the  $d(e,e'p)n$  reaction in the Impulse Approximation. This calculation employs the formalism of Dmitrasinovic and Gross.<sup>[18]</sup> Note that this option is explicitly for  $(e,e'p)$  and selecting  $(e,e'n)$  at runtime will not override this. Note also that these routines, although they appear to give reasonable results for both the cross section and proton polarizations, have not been fully tested.

### 7.4 Pion Electroproduction from the Proton (Option 500)

This option computes cross section and recoil polarization observables for pion electroproduction on the proton in  $p(e,e'p)\pi^0$  using the routines of R.W. Lourie.<sup>[19]</sup> It uses the helicity amplitude formalism and includes the nucleon pole (Born) terms. The amplitudes for the  $\Delta$  and higher resonances are taken from the dispersion relation based parameterization of Devenish and Lyth.<sup>[20]</sup> The user may also employ a set of external Roper amplitudes supplied via files. If Option 500 is selected, the user must supply the name of a file which contains various resonance options and parameters. A "standard" resonance option file is located in DAT\$D and is called "res\_standard.dat".

## Chapter 8

### MODIFYING THE PROGRAM

MCEEP was written in a way that allows the user to modify the program with minimal effort. Of course, not all potential implementations of MCEEP could be anticipated. However, special attention has been paid to the two areas which will likely need to be specifically tailored for any user. These are: adding new histogram variables and incorporating new physics models. The required changes to the program for each of these cases is now described.

#### 8.1 Adding a New Histogram Variable

All histogram variables are calculated in the subroutine KINEM. This routine is called in the calculation of the default variable ranges (subroutine RANGES) as well as in the main Monte Carlo loop (the main routine, MCEEP). Thus, new variables need only to be added to subroutine KINEM. So that the other routines have access to the new variable the Fortran INCLUDE file, "CMN\$D:VAR.CMN", must also be modified. There are four steps that need to be completed (if there is any confusion just look at one of the existing variables in the VAR.CMN file and do likewise):

#### VAR.CMN

- i) Declare the new variable as DOUBLE PRECISION.
- ii) Update NUM\_VAR in the DATA statement to reflect the new number of variables.
- iii) Equivalence the new variable to the next element of the array VAR. When requesting histograms or placing cuts within the input file, the variable is referenced via the index in this array.
- iv) Choose a name for the variable and add this to the list of DATA statements for the array VAR\_NAME. This name is only needed for the output summary file so that the formatted output displays a mnemonic for each variable.

**Note:** Make sure the new variables are added to the end of the list. It is suggested that the existing variables are not modified or removed since some of them are used in the calculation of cross sections. In addition, the formatted output produced by subroutine SUMMARY requires that the indices of the existing variables not change, since these indices are referenced directly in one of the WRITE statements. Finally, it is suggested that all subroutines which include VAR.CMN be recompiled.

In summary, the following steps must be taken as described above:

- 1) Add the calculation of the new variable in subroutine KINEM.
- 2) Modify the include file VAR.CMN as described in steps i) through iv) above.
- 3) Recompile all routines which include VAR.CMN
- 4) Relink the new object modules using LINK.COM

## 8.2 Incorporating New Physics Models

There are two subroutines which need to be changed to add a new physics model, PHYS\_CHOICE and PHYSICS.

PHYS\_CHOICE is called by MCEEP before the Monte Carlo event loop. This routine allows the user to select the physics model at run-time and it also performs any preliminaries such as opening and reading files. For instance, if one of the factorized (e,e'N) models is chosen, PHYS\_CHOICE calls the subroutine SPECT\_SETUP which then asks the user to select a spectral function so that other preliminaries may be performed. Thus, the first step in incorporating a new physics option is to add the option to the list of selections in PHYS\_CHOICE. As is done for the existing options, any required files should be opened and read within this routine. The new option must have a unique selection number associated with it, which will be referenced by the variable, IPHYS\_OPT.

All cross sections (other than single-arm) and polarizations are returned by the subroutine PHYSICS, which is called within the main event loop in MCEEP. This routine must be modified so that the user's physics subroutine is called under the appropriate IPHYS\_OPT number. The new physics routine should return SIGMA\_EEP (the coincidence cross section) as well as POL\_N, POL\_L and POL\_T (the parts of the cross section which correspond to the three ejectile spin orientations) and ASYMMETRY (the electron analyzing power) if these observables are calculated. Note that the "polarizations" computed by the new user routine are not polarizations in the usual sense; rather they are the pieces of the cross section which correspond to the three spin orientations. MCEEP will calculate the polarizations from these automatically by dividing these arrays by the unpolarized cross section array, channel by channel, if the user requests histograms of average polarization within the input file. The quantities computed by the physics routine should have units of  $\text{fm}^2/\text{sr}^2/\text{MeV}$  for a bound state (5-fold differential) or  $\text{fm}^2/\text{sr}^2/\text{MeV}^2$  for continuum states (6-fold differential). In computing the yields, MCEEP multiplies these cross sections by the appropriate "SIGFACTOR" (depending on whether it is bound state or continuum). The units of SIGFACTOR are  $\text{sr}^2\text{MeV}/\text{fm}^2$  (bound state) or  $\text{sr}^2\text{MeV}^2/\text{fm}^2$  (continuum). Thus, the yields are dimensionless as required.

If the user wishes to add a new spectral function for one of the existing factorized (e,e'N) models, only the routines SPECT\_SETUP and SPECTRAL need to be modified. In SPECT\_SETUP the new option should be added to the list of choices and a unique index should be associated with the choice as referenced by the variable ISPEC\_OPT. Also, any necessary preliminaries such as opening and reading files should be performed

by calling a user routine from SPECT\_SETUP. Then a piece should be added to the routine SPECTRAL so that the new spectral function is calculated every event. The units of the function SPECTRAL should be  $\text{MeV}^{-3}$  for a bound state or  $\text{MeV}^{-4}$  for the continuum case.

In summary, the following steps should be taken to add new physics models or spectral functions to MCEEP:

#### New Physics Model

- 1) Add option to the list in PHYS\_CHOICE. Associate unique integer identifier (IPHYS\_OPT) with the new option.
- 2) Perform preliminaries (open files, etc.) in PHYS\_CHOICE.
- 3) Perform calculation of SIGMA\_EEP and optionally POL\_N, POL\_L, POL\_T and ASYMMETRY by calling a user subroutine from subroutine PHYSICS. These quantities should have units of  $\text{fm}^2/\text{sr}^2/\text{MeV}$  (for bound state) or of  $\text{fm}^2/\text{sr}^2/\text{MeV}^2$  (for continuum).

#### New Spectral Function

- 1) Add option to the list in SPECT\_SETUP. Associate unique integer identifier with the new option (ISPEC\_OPT).
- 2) Perform preliminaries (open files, etc.) in SPECT\_SETUP.
- 3) Perform calculation of SPECTRAL by calling a user subroutine within function SPECTRAL. SPECTRAL should have units of  $\text{MeV}^{-3}$  (bound state) or  $\text{MeV}^{-4}$  (continuum).

## Appendix DESCRIPTION OF KINEMATIC VARIABLES

MCEEP allows for histograms of any of the weighting functions (singles cross sections, coincidence cross sections, phase space, etc.) vs. various kinematic variables. Although the user can easily add kinematic variables to the list, it is suggested that none of the standard ones be removed. This is because some of these variables are used by the various cross section calculation routines. A table of the standard kinematic variables follows. Each variable is then described in detail.

| Index | Variable      | Default Units        |
|-------|---------------|----------------------|
| 1     | $x_e$         | meters               |
| 2     | $\theta_e$    | radians              |
| 3     | $y_e$         | meters               |
| 4     | $\phi_e$      | radians              |
| 5     | $z_e$         | meters               |
| 6     | $p_e$         | MeV/c                |
| 7     | $x_p$         | meters               |
| 8     | $\theta_p$    | radians              |
| 9     | $y_p$         | meters               |
| 10    | $\phi_p$      | radians              |
| 11    | $z_p$         | meters               |
| 12    | $p_p$         | MeV/c                |
| 13    | $E_0$         | MeV                  |
| 14    | $\theta_s$    | radians              |
| 15    | $\omega$      | MeV                  |
| 16    | $ \vec{q} $   | MeV/c                |
| 17    | $\theta_q$    | radians              |
| 18    | $\phi_q$      | radians              |
| 19    | $q_\mu^2$     | (GeV/c) <sup>2</sup> |
| 20    | $x$           | dimensionless        |
| 21    | $\epsilon$    | dimensionless        |
| 22    | $\theta_{pq}$ | radians              |
| 23    | $\phi_z$      | radians              |
| 24    | $\epsilon_m$  | MeV                  |
| 25    | $p_r$         | MeV/c                |
| 26    | $ \vec{p}_r $ | MeV/c                |
| 27    | $f_{rec}$     | dimensionless        |
| 28    | $W$           | MeV                  |
| 29    | $\theta_{CM}$ | radians              |

Index: 1

Variable:  $x_e$

Fortran Name: BEAM\_E1

Default Units: meters

Description: The  $x$  coordinate of the origination point within the target of the scattered electron referred to the "laboratory" coordinate system (see the text).

Index: 2

Variable:  $\theta_e$

Fortran Name: TH\_E\_I

Default Units: radians

Description: The vertical angle of the scattered electron at the target referred to the "laboratory" coordinate system (see the text).

Index: 3

Variable:  $y_e$

Fortran Name: BEAM\_E2

Default Units: meters

Description: The  $y$  coordinate of the origination point within the target of the scattered electron referred to the "laboratory" coordinate system (see the text).

Index: 4

Variable:  $\phi_e$

Fortran Name: PH\_E\_I

Default Units: radians

Description: The horizontal angle of the scattered electron at the target referred to the "laboratory" coordinate system (see the text).

Index: 5

Variable:  $z_e$

Fortran Name: BEAM\_E3

Default Units: meters

Description: The  $z$  coordinate of the origination point within the target of the scattered electron referred to the "laboratory" coordinate system (see the text).

Index: 6  
Variable:  $p_e$   
Fortran Name: PF\_E\_I  
Default Units: MeV/c  
Description: The momentum of the scattered electron.

Index: 7  
Variable:  $x_p$   
Fortran Name: BEAM\_P1  
Default Units: meters  
Description: The  $x$  coordinate of the origination point within the target of the emerging hadron referred to the "laboratory" coordinate system (see the text). This is the same as  $x_e$  (BEAM\_E1) since the electron and hadron originate from the same point.

Index: 8  
Variable:  $\theta_p$   
Fortran Name: TH\_P\_I  
Default Units: radians  
Description: The vertical angle of the emerging hadron at the target referred to the "laboratory" coordinate system (see the text).

Index: 9  
Variable:  $y_p$   
Fortran Name: BEAM\_P2  
Default Units: meters  
Description: The  $y$  coordinate of the origination point within the target of the emerging hadron referred to the "laboratory" coordinate system (see the text). This is the same as  $y_e$  (BEAM\_E2) since the electron and hadron originate from the same point.

Index: 10  
Variable:  $\phi_p$   
Fortran Name: PH\_P\_I  
Default Units: radians  
Description: The horizontal angle of the emerging hadron at the target referred to the "laboratory" coordinate system (see the text).

Index: 11  
Variable:  $z_p$   
Fortran Name: BEAM\_P3  
Default Units: meters  
Description: The  $z$  coordinate of the origination point within the target of the emerging hadron referred to the "laboratory" coordinate system (see the text). This is the same as  $z_e$  (BEAM\_E3) since the electron and hadron originate from the same point.

Index: 12  
Variable:  $p_p$   
Fortran Name: PF\_P\_I  
Default Units: MeV/c  
Description: The momentum of the emerging hadron.

Index: 13  
Variable:  $E_0$   
Fortran Name: E0\_I  
Default Units: MeV  
Description: The energy of the incident electron after offsets and resolution smearing of the beam.

Index: 14  
Variable:  $\theta_e$   
Fortran Name: TSCAT  
Default Units: radians  
Description: The electron scattering angle.

Index: 15  
Variable:  $\omega$   
Fortran Name: OMEGA  
Default Units: MeV  
Description: The electron energy transfer.

Index: 16  
Variable:  $|\vec{q}|$   
Fortran Name: QMAG  
Default Units: MeV/c  
Description: The magnitude of the 3-momentum transfer.

Index: 17  
Variable:  $\theta_q$   
Fortran Name: THEQ  
Default Units: radians  
Description: The vertical angle of  $\vec{q}$  with respect to the "laboratory" coordinate system.

Index: 18  
Variable:  $\phi_q$   
Fortran Name: PHIQ  
Default Units: radians  
Description: The horizontal angle of  $\vec{q}$  with respect to the "laboratory" coordinate system.

Index: 19  
Variable:  $q_\mu^2$   
Fortran Name: QMU2  
Default Units:  $(\text{GeV}/c)^2$   
Description: The square of the electron 4-momentum transfer.

Index: 20  
Variable:  $x$   
Fortran Name: X  
Default Units: dimensionless  
Description: The Bjorken  $x$  variable,  $x = q_\mu^2/2m$ .

Index: 21  
Variable:  $\epsilon$   
Fortran Name: EPSILON  
Default Units: dimensionless  
Description: The longitudinal polarization of the virtual photon ( $0 \leq \epsilon \leq 1$ ), given by:  $\epsilon = 1/(1 + 2|\vec{q}|^2 \tan^2(\theta_s/2)/q_\mu^2)$ .

Index: 22  
Variable:  $\theta_{pq}$   
Fortran Name: THETA\_PQ  
Default Units: radians  
Description: The angle between the emerging hadron and  $\vec{q}$ .

Index: 23  
Variable:  $\phi_z$   
Fortran Name: PHIX  
Default Units: radians  
Description: The out-of-plane angle (i.e. the angle between the electron scattering plane and the plane containing  $\vec{q}$  and the emerging hadron).

Index: 24  
Variable:  $\epsilon_m$   
Fortran Name: MISS\_M  
Default Units: MeV  
Description: The missing mass (i.e. excitation energy of the residual nuclear system).

Index: 25  
Variable:  $p_r$   
Fortran Name: PREC  
Default Units: MeV/c  
Description: The momentum of the recoiling nuclear system. This quantity is negative if the recoil momentum has a component along  $\vec{q}$ :  $p_r = -\vec{p}_r \cdot \vec{q} / |\vec{p}_r \cdot \vec{q}|$ .

Index: 26  
Variable:  $|\vec{p}_r|$   
Fortran Name: PRMAG  
Default Units: MeV/c  
Description: The magnitude of the recoil momentum.

Index: 27  
Variable:  $f_{rec}$   
Fortran Name: RECFAC  
Default Units: dimensionless  
Description: The recoil factor. This is a Jacobian which is applied for bound states so that the resulting cross section is five-fold differential instead of six-fold (an integration over the bound state missing mass results in this Jacobian).

Index: 28  
Variable:  $W$   
Fortran Name: W  
Default Units: MeV  
Description: The invariant mass of the hadronic final state.

Index: 29

Variable:  $\theta_{CM}$

Fortran Name: THETA\_CM

Default Units: radians

Description: The angle of the ejectile with respect to  $\bar{q}$  in the center-of-mass system.

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