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**Differential Production Cross Sections of
Multiply Charged Fragments in 800 MeV
Proton-Induced Spallation of Carbon,
Aluminum, and Nickel**

University of California

LOS ALAMOS SCIENTIFIC LABORATORY

Post Office Box 1663 Los Alamos, New Mexico 87545

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Steven Craig Luckstead

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DIFFERENTIAL PRODUCTION CROSS SECTIONS OF MULTIPLY CHARGED
FRAGMENTS IN 800 MeV PROTON-INDUCED SPALLATION
OF CARBON, ALUMINUM, AND NICKEL

ABSTRACT

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Washington State University, 1978

Chairman: Gerald E. Tripard

Differential production cross sections for multiply charged fragments from 800 MeV proton-induced spallation of ^{12}C , ^{27}Al , and natural Ni have been measured at 30 and 90 degrees. The ion fragments were identified using a time-of-flight, ΔE -E detector telescope capable of complete particle identification for energies as low as .25 MeV/nucleon. The very short ranges of the particles of interest required the construction of very thin detectors with minimal deadlayer material. The time-pick-off detectors and gas ionization chamber developed are unique, and represent the state-of-the-art in fast timing for time-of-flight measurements and in construction of thin detectors.

The resolutions achieved allowed the cross sections of ^3He , ^4He , ^6Li , ^7Li , ^7Be , ^9Be , ^{10}Be , ^{10}B , ^{11}B , ^{11}C , ^{12}C , and ^{13}C to be determined, along with those of nitrogen and oxygen without isotope separation. The cross sections were found to have weak angular dependence. Consequently, pseudo cross sections were calculated from the 90° data by integrating the differential cross sections from 0 to 25 MeV for each product and multiplying by 4π.

Pseudo theoretical cross sections were similarly calculated from theoretical differential cross sections. These differential cross sections were calculated using a Monte Carlo computer code which incorporated the

cascade-evaporation model of high energy nuclear reactions. Implications are drawn for modifications of the model. The results suggest reducing the transparency of the struck nucleus to pions produced in the cascade stage of the reaction model in order that a higher excitation energy be left for the evaporation stage. Also, there is some evidence that evaporations of nuclear aggregates more massive than ${}^4\text{He}$ occur. Inclusion of such evaporations should improve the model.

CHAPTER 1

INTRODUCTION

The differential production cross sections were measured for spallation fragments from light nuclei on bombardment with 800 MeV protons and the results were used to check on the extent of validity of present reaction models and computer codes. Most attempts at theoretical calculations of this type of cross-section have been made for intermediate and high atomic mass targets bombarded with nucleons or mesons.¹⁻¹³ The particle spectra measured in the present experiment, from the target nuclei of carbon, aluminum and nickel, will indicate the extent to which these models are valid for light nuclei. Also, the techniques and apparatus developed for the complete identification of low-energy nuclear fragments represent an enhancement in detection sensitivity for very short-range particles.

Theoretical Model of Spallation

Spallation encompasses several processes, all of which entail nuclear reactions where the target nucleus is broken up into several fragments upon bombardment with, in this case, energetic protons. Processes of this type include:

- (1) Intra-nuclear cascade, resulting in the emission of cascade particles;
- (2) Evaporation of particles from the excited residual nucleus;
- (3) Fragmentation; and
- (4) Fission.

The first two of these processes are expected to predominate in light nuclei at the reaction energy studied here. The course of such a high energy reaction is thought of as proceeding in two stages as shown schematically in Fig. 1.1. The first stage entails the fast processes of inelastic collisions between an incident proton and nucleons within the target nucleus, and the subsequent intranuclear cascade which gives rise to emission of cascade particles and the formation of a highly excited residual nucleus. In the second stage the slower process of evaporation of fragments from the excited nucleus takes place. This de-excitation is conceived of as being an evaporation process from a hot Fermi gas.¹⁴

The statistical model of particle emission that accounts for the de-excitation suggests continuous energy spectra for these fragments and their heavier recoil residues. Figure 1.2 shows hypothetical emission and recoil spectra of this kind. The low-energy falloff in the evaporation spectrum is caused by the Coulomb barrier preventing the escape of low energy charged fragments. Since the internal nucleon energy distribution within the excited residual nucleus is assumed to be Maxwellian, the high-energy falloff arises from the small probability of concentrating a large amount of energy on a given nucleon or cluster of nucleons in the "hot" nuclear matter. Those charged particles which are emitted by the evaporation mechanism are, therefore, expected to have energies of the order of the Coulomb barrier. The heavier residues of the spallation will have recoil momenta of the order of the Fermi momentum. The resulting energy distribution ought to monotonically fall, with the distribution having a width given by

$$\left(\frac{M_{\text{Target}} - M_{\text{Fragment}}}{M_{\text{Fragment}}} \right) E_{\text{Fermi}}.$$

Fig. 1.1.--Schematic Diagram of Two Stage High Energy Reaction

Fig. 1.2.--Hypothetical Emission and Recoil Spectra

This expression gives the distribution width in terms of the Fermi energy and the masses of the target and fragment. Order of magnitude estimates from this model suggest energies on the order of 0.5 to 1.0 MeV/nucleon, and these estimates are supported by existing data.

The Experimental Problem and Solution

The difficulties in complete identification of such low energy, and consequently short range, particles accounts for the scarcity of data. Conventional techniques using ΔE -E counter telescopes are limited to energies greater than 2 MeV/nucleon. The objective of this experiment was to completely identify those nuclear fragments with charges in the range $Z=2$ to 8. Achievement of mass resolution adequate for clean separation of each isotope allowed generation of an energy spectrum for each species with energies down to approximately .25 MeV/nucleon. The requirement for complete identification of these short-ranged multiply charged fragments dictates that one use detectors that have poor efficiencies in the detection of more lightly ionizing particles such as protons, deuterons and tritons. Hence, these last particles were not studied, nor was any attempt made to detect mesons or neutrons.

In order to achieve the objective of complete identification of short ranged nuclear fragments it was necessary to construct a very thin detector system. The system built was capable of resolving the charge, mass and energy of all of the isotopes of helium through oxygen in the range of E/M from approximately .25 MeV/nucleon to 5 MeV/nucleon. This was done with a time-of-flight (TOF), ΔE -E counter telescope. Each telescope component was constructed with the minimum of deadlayer material, that is, stopping material through which the ion fragments passed, but which yielded no direct

signals reflecting energy losses of the fragments. The telescope shown schematically in Fig. 1.3, consisted of two time-pick-off detectors, T_1 and T_2 , for a time-of-flight measurement, followed by a gas ionization chamber, ΔE , two transmission silicon detectors, E_1 and E_2 , and a nontransmitting silicon veto counter, V .

The identification scheme follows. The time-pick-off detectors measured the fragment time-of-flight over a flight path of known length. This determined the particle velocity, v , which, for non-relativistic particles, is simply related to the particle energy, E , and mass, M , by

$$v^2 = 2 E/M. \quad (1.1)$$

Consequently, the particle mass was determined from measurement of the energy and TOF of the particle. The fragment energy was taken as the sum of energies deposited in the ΔE , E_1 and E_2 detectors, plus a correction due to the deadlayers of the telescope.

The gas ionization chamber served as a thin transmission detector which measured the rate of energy loss of the particles passing through the gas. This rate of energy loss is approximately given by the simplified Bethe-Bloch equation¹⁵

$$-\frac{dE}{dx} = \left(\frac{a Z_{eff}^2 c^2}{v^2} \right) \ln [bv^2 / (c^2 - v^2)], \quad (1.2)$$

where c is the speed of light, and a and b are constants dependent on the detector material. Z_{eff} is the effective charge state of the moving ion, reflecting the fact that the ion may not be fully stripped of its atomic electrons. The logarithmic term varies slowly with energy, and so, neglecting its effect and substituting Eq. (1.1), one has

Fig. 1.3.--Time-of-Flight, ΔE -E Counter Telescope Schematic

$$\frac{dE}{dx} \propto \frac{MZ^2}{E} \quad (1.3)$$

Measurement of dE/dx , along with the aforementioned mass and velocity (E/M), uniquely determined Z . Hence, the detector telescope measuring TOF, E and dE/dx was capable, in principle, complete identification of the charged reaction products of interest given that adequate resolutions for the various measurements could be achieved.

A discussion of the constraints imposed by the desired sensitivities and resolutions follows. The mass resolution was determined by the TOF resolution and total energy resolution in the following way

$$\left(\frac{\delta M}{M}\right)^2 = \left(\frac{\delta E}{E}\right)^2 + 4\left(\frac{\delta t}{t}\right)^2 \quad (1.4)$$

The total energy resolution of the telescope, as measured with a monoenergetic alpha source, was $\delta E/E = .012$, reflecting a full-width-at-half-maximum (FWHM) of .65 keV. The time resolution measured with this source was $\delta t/t = .013$, with a FWHM of 250 picoseconds. This suggested a mass resolution of $\delta m/m = .029$. Direct measurement of the mass resolution from data gave a value of approximately .05. These resolutions were more than adequate for the stated objectives of the experiment, imposing no unplanned constraints on the mass identification.

Since the charge identification was made from the ΔE and E/M measurements, the Z resolution was a function of these two variables. Also, the data reduction and analysis computer routine used in the determination of the charge required that the particle mass be calculated as a prerequisite to the charge identification. This coupled the charge resolution to the mass resolution. However, in most instances the Z resolution was most strongly influenced by the resolution in the ΔE measurement. This resolution was

measured with the alpha-particle source to be 0.18. Direct measurement of the Z resolution from data yielded a FWHM of 0.14 atomic charge units. This, again, was sufficient to resolve those charges of interest and posed no unplanned constraints. The charge resolution was initially complicated, however, by lack of reliable stopping power data. A particle charge was determined by comparing the measured energy loss in the ionization chamber with expected losses of various species with the same particle velocity. Adequate tables of these expected energy losses for heptane were unavailable and had to be generated from the data itself in order to extract the maximum intrinsic resolution of the system.

For complete identification a particle would have to be sufficiently energetic to penetrate the telescope to the point of making a registration in the E_1 detector. The thickness of the intervening deadlayers and detector active volumes was $330 \mu\text{g}/\text{cm}^2$. Fragments sufficiently energetic as to punch through the E_2 detector and register in the veto counter were not recorded as events. The thickness of the telescope through the active volume of the E_2 detector was approximately $19 \text{ mg}/\text{cm}^2$. Hence, fragments with ranges between these two limits were detectable and the corresponding domain of particle energies were those of interest to the investigation proposed.

Two other considerations which relate to the performance are the efficiency and the acceptance of the telescope for the particles studied. These subjects are discussed in detail in Chapter 3, but I will make a few qualitative remarks here. The efficiency studies for the time-pick-off detectors indicated that the efficiencies could be correlated to, and expressed solely as a function of the amplitude of the ΔE signal from the ionization chamber. Energy depositions in the ΔE detector greater than 0.6 MeV corresponded to efficiencies better than 95 percent in the time-pick-off

detectors. This meant that most efficiency corrections were small for those species with Z greater than two.

A Monte-Carlo computer code was written to account for multiple scattering effects within the telescope as well as perturbations of the trajectories of the charged fragments through the telescope by the magnetic fields associated with the time-pick-off detectors. These corrections proved to be greatest for low velocities and for those species with the greater charge-to-mass ratios.

Chapter 2 deals with the conditions and apparatus of the experiment, including the physical layout of the experiment, the design and construction of the detectors, and the electronics and data acquisition system. In Chapter 3 the data analysis is discussed. This includes the data reduction, the particle identification scheme, resolutions, corrections to the spectra due to efficiencies, telescope acceptance, and effects caused by the target, and generation of the absolute cross sections. The theoretical model and computer code used to generate predictions of the production cross sections are presented in Chapter 4. Finally, Chapter 5 gives the results of the experiment and an interpretation of those results.

CHAPTER 2

EXPERIMENT AND APPARATUS

Physical Layout

The experiment was performed with the 800 MeV proton beam of line B at the Clinton P. Anderson Meson Physics Facility (LAMPF). A 30.5 cm diameter evacuated scattering chamber was situated in the beam line in the line B cave. Figure 2.1 shows the location of the experiment in the beam line just downstream from three quadrupole magnets and upstream of the liquid deuterium target.

The spallation fragments were identified in a time-of-flight, $\Delta E-E$ telescope that was mounted on a movable carriage. The general layout of the scattering chamber, detector assembly and vacuum system is illustrated in Figs. 2.2 and 2.3. The general features of these experimental components, along with the beam monitoring, the characteristics of the beam and the monitor telescope, are discussed in this section. The design and operation of the specific detectors making up the telescope are discussed in the following section.

The telescope could be joined to the scattering chamber at ports situated at 30° , 60° , 90° , 120° , and 150° to the beam. During the course of the experiment, only the 30° and 90° ports were used due to beam time restrictions. A target ladder with six target positions was mounted in the scattering chamber. The ladder consisted of a rectangular aluminum frame with inside dimensions of 15.24 cm by 29.21 cm. One mil aluminized Kapton

Fig. 2.1.--Location of Experiment in Line B

Fig. 2.2.--Top View of Scattering Chamber and Detector Assembly

Fig. 2.3.--Side View of Scattering Chamber, Detector Assembly and Vacuum System.

was stretched over the frame with 2.54 cm diameter holes punched at 3.81 cm intervals congruent with the long axis of the frame. These served as the target mounts. The following targets were mounted over three of the apertures: a $270 \mu\text{g}/\text{cm}^2$ aluminum foil, a $550 \mu\text{g}/\text{cm}^2$ nickel foil, and a $135 \mu\text{g}/\text{cm}^2$ CH_2 foil. One position was used as a blank for background or target-out runs. Thicknesses of the various targets were determined by measuring the energy loss of 5.48 MeV alpha particles on passage through the target. To prevent charge build-up on the target the Kapton mount was made conducting with a very thin aluminum film on its surface. The targets were made to adhere to the mount with a thin film of vacuum grease.

The telescope consisted of three detector chambers separated from one another during operation by the thin windows of the ionization chamber. The detector chamber closest to the scattering chamber housed the time-pick-off detectors which measured the time-of-flight (TOF) of the fragments. The flight path of fragments between the foils of these detectors was 30.5 cm, with the foil of the first, T_1 , detector situated 52.1 cm from the center of the target. Vacuum was maintained in this chamber at approximately 1×10^{-6} Torr by a VacIon pump with a 500-l/sec pumping capacity.

The second chamber adjoining the back of the TOF chamber was separated from it by an aluminized cellulose acetate window $56 \mu\text{g}/\text{cm}^2$ thick. This window was 15.08 cm behind the foil of the T_2 detector. This ionization chamber, or ΔE chamber, was cylindrically constructed with gas flow ports on either side and an evacuation port on the bottom which was connected to a manifold joined to the TOF chamber for use in simultaneous pump-down and let-up of the system. During operation the ionization chamber was maintained at a constant pressure and the gas was circulated at a rate of approximately $2 \text{ cm}^3/\text{sec}$ by a flow system. The axial length of this chamber, front window to back, was 2.25 cm.

The last chamber, housing the stack of solid state detectors, was, again, separated from the ionization chamber by a $50 \text{ } \mu\text{g}/\text{cm}^2$ aluminized window. This chamber supported the E_1 transmission detector 2.3 cm behind the ionization chamber window, the E_2 transmission detector 1.3 cm behind the E_1 , and the veto, V, counter 1.3 cm behind the E_2 . An event was taken to be a coincidence between the T_1 , T_2 , and E_1 detectors, and since E_1 was the most distant of these detectors from the target, its sensitive surface area defined the solid angle of the telescope. The sensitive surface was a 1.0 cm^2 circular area and its displacement from the target was 102.23 cm. This gave a geometrical solid angle of 7.61×10^{-6} steradians. Vacuum was maintained in this chamber by a Welch mechanical pump with a refrigerated cold trap. A valve could be opened between the ΔE chamber and the solid state chamber for simultaneous pump-down or let-up of the entire telescope. This chamber was typically maintained at 50 microns pressure during operation.

A plastic scintillator monitor telescope was aligned so as to subtend a solid angle with the target. This was done through a glass port on the scattering chamber at 30° from the forward direction on the opposite side of the beam line from the TOF- ΔE -E telescope. The three counter telescope was used to measure the dead-time of the data acquisition system. This was done by scaling both a monitor coincidence which was bin gated and the same coincidence ungated.

The scattering chamber was situated 4.5 m upstream of line B current monitor, or toroid, number 2. The nearest wire scanner, number 4, was 1.05 m downstream of the target position. These were the primary beam monitors used to measure the integrated current on the target and the beam spot profile.

The location of the scattering chamber in the beam line proved to be poor for the purpose of obtaining a suitable tune. The vertical tune was

quite good, giving a beam spot with a full-width-at-half maximum (FWHM) of approximately 2.2 mm. The horizontal tune was much less satisfactory, being diffuse and unstable. Often the wire scanner profile was so broad and weak, or so irregular in shape, that a peaked distribution, as was seen in the vertical profile, was hardly discernable. These deteriorated conditions had no identifiable source in the beam tune, as the tune would be unaltered from earlier profiles where the beam spot had been adequate. Wire scan profiles further upstream and downstream did not show the profile instabilities seen at wire scanner number 4. At this position in the beam line it was particularly difficult to achieve a neat narrow beam in the horizontal without effecting a severe deterioration of the beam tune further downstream. Consequently, it was often necessary to accept a diffuse horizontal beam spot whose profile was difficult to monitor at low-beam currents. Profiles upstream and downstream indicated that the overall tune of the beam line was more stable than was indicated solely by the profiles from the nearest wire scanner. The beam spot profile is discussed further in Chapter 3.

The singles rates in the channel plates were also sensitive to the quality of the horizontal tune, especially at the 30° forward angle. In order to keep pile-up to a minimum, care had to be taken to keep the channel plate instantaneous singles rates below approximately 2×10^5 counts per second. Depending upon the quality of the tune, this was frequently the limiting factor on the beam current that could be handled. Most data were collected in the range of average beam current between 100 and 300 nA.

Finally, the counting house was located one floor above the line B tunnel. Signal and power cables extended 46 m from a distribution panel mounted on a rack alongside the experiment to the counting house. All signal cables from the detectors and test signal cables to the detectors were shielded cables of the type RG 214/U.

Detectors:

Time-Pick-Off Detectors:

The time pick-off detectors, T_1 and T_2 , used in the time-of-flight measurement worked by detecting secondary electrons emitted upon passage of an ion fragment through $20 \mu\text{g}/\text{cm}^2$ carbon foils. These secondary electrons were isochronously transported by crossed electric and magnetic fields to impinge upon Channeltron Electron Multipliers. The secondary electrons were accelerated in an electric field of $2.778 \times 10^5 \text{ V/m}$ and were bent out of the ion beam by a 0.0125 T magnetic field. The two detectors were placed on a line from the target so as to give a 30.5 cm flight path between the carbon foils.

The time resolution of such a system is contingent upon (1) ion time-of-flight differences caused by variations in flight path lengths, (2) time-of-flight differences for electrons emitted from different parts of the foil, (3) electrons emitted with different initial velocities, and (4) dispersion introduced by the detection system itself, i.e. the electron multipliers. Achievement of a time resolution of approximately 200 psec was deemed more than adequate for the proposed measurement. With ion velocities on the order of 1 cm/nsec , variations in flight paths had to be minimized. Thus, the carbon foils were mounted perpendicular to the ion beam direction and their cross-sectional dimensions were small compared with the ion flight path. Time dispersion due to variations in initial electron velocities and flight time differences of electrons emitted from different parts of the foil were reduced by using a large accelerating potential and by suitable design of the electron optics. These optics are described below. The use of the Chevron type channel plate electron multiplier minimizes the time dispersion

in the electron multiplier phase. Jitter in transit time for the electron multiplication process is estimated by the manufacturer to be less than 100 psec.¹⁶

The detector is shown in Fig. 2.4 and a schematic follows in Fig. 2.5. Fragments coming from the target encountered a $20 \mu\text{g}/\text{cm}^2$ carbon foil with a $4 \mu\text{g}/\text{cm}^2$ cellulose acetate backing for support. The foil was mounted on a 1.0 cm diameter aperture centered on a metal disc which was maintained at a high negative potential, typically -2296 V. Behind this was a series of rectangular metal frames joined by a resistor chain that served to maintain a homogeneous electric field in the region within these frames. The positive high voltage plane then followed. This was a solid metal plane except for a 1.0 cm diameter aperture which was concentric with the aperture on the negative potential plane. This plane was typically maintained at +4949 V. The channeltron electron multiplier was situated adjacent to the disc with the carbon foil, with its active surface being parallel to the plane of this disc and facing into the volume defined by the rectangular guard rings. The secondary electrons were transported through this volume by the electric field generated across the high voltage planes and a magnetic field generated by permanent magnets. All of the detector apparatus described above was secured between the pole plates of a permanent magnet. The plates were steel, joined at either end by aluminum blocks which were drilled out with ten 1.0 cm diameter columns. These columns contained stacks of seven pill-box shaped permanent magnets which were the source of the magnetic field. The magnetic field was mapped and the pole plates were shimmed in order to achieve uniformity. The integral magnetic field was also measured along the line of the heavy ion trajectories. This last measurement was made with a flip-coil apparatus and the results gave integral fields of 0.00298 T-m

Fig. 2.4.--Time-Pick-Off Detector

Fig. 2.5.--Cut Away Drawing of Time-Pick-Off Detector

and 0.00291 T-m for the T_1 and T_2 detectors respectively. The corresponding effective lengths of the field were calculated from these values and the central field strength and were found to be 0.234 m and 0.235 m. The use of these last pieces of information to calculate the effects on telescope acceptance of the perturbation of the ion trajectories by the magnetic fields is discussed in Chapter 3.

The design of the electron transport system had the constraints that the transit time fluctuations of the secondary electrons had to be minimized and the energy of the electrons had to be sufficient that their detection efficiency was large. The following discussion deals with each of these matters. As illustrated in Fig. 2.6 a coordinate system was chosen such that the z-axis was perpendicular to the plane of the carbon foil and the crossed electric (E) and magnetic (B) fields were in the minus z and plus x directions, respectively. The equations of motion for an electron of charge-e and mass m are given by:

$$x(t) = x(o) + v_x(o)t \quad (2.1)$$

$$y(t) = y(o) - \frac{v_z(o)}{\omega} [1 - \cos \omega t] + \frac{[v_y(o) + E/B]}{\omega} \sin \omega t - (E/B)t \quad (2.2)$$

$$z(t) = z(o) + \frac{[v_y(o) + E/B]}{\omega} [1 - \cos \omega t] + \frac{v_z(o) \sin \omega t}{\omega}, \quad (2.3)$$

where $\omega = eB/m$, is the cyclotron frequency and, for example, $x(o)$ and $v_x(o)$ are the initial x components of position and velocity as the electron emerges from the carbon foil. These equations of motion describe a cycloidal path with a period $[z(\tau) = z(o)]$ of:

$$\tau = 2\pi/\omega.$$

Fig. 2.6.--Coordinate System for Electron Transport Equations of Motion

The transverse displacement (D) of the electrons is given by:

$$D = y(\tau) - y(0) = \frac{2\pi m}{e} \frac{E}{B^2} . \quad (2.4)$$

Choosing the magnitudes of the fields E and B to be 2.778×10^5 V/m and 0.0125 T respectively, the trajectory has a maximum transverse displacement of 2π cm and a maximum z displacement of about 2 cm, with τ being 2.95×10^{-9} sec.

It can be seen from Eq. (2.3) that, since the flight time is independent of $x(0)$ and $y(0)$, the time dispersion of the electrons in the system is independent of the origin of the electrons on the carbon foil. The dispersion is due solely to the spread in knockout velocities of the emerging secondary electrons. These velocities will be on the order of 10^8 cm/sec, which corresponds to the most probable electron knockout energy of a few electron volts. Noting that E/B is a velocity, an estimate can be made of the time dispersion. The selected field values give a value of E/B of about 2×10^9 cm/sec. From Eq. (2.3) the time dependence of the electron position is seen to be dominated by the value of E/B and not the initial velocity components. The expected fluctuations in flight times are approximately given by:

$$\frac{1}{\omega} \frac{v(0)}{(E/B)} \approx 25 \text{ psec.} \quad (2.5)$$

In a more detailed treatment of the time dispersion, the actual geometry of the transport system had to be considered. This geometry was also dictated by the additional constraint that the electrons impinge upon the electron detector with sufficient energy for optimal detection efficiency. This necessitated the displacement of the detector face relative to the plane of the carbon foil. With a displacement h in the z direction,

the arrival time of the secondary electrons at the detector surface would be governed by the relation:

$$h = \frac{v_y(o) + E/B}{\omega} [1 - \cos \omega t] + \frac{v_z(o)}{\omega} \sin \omega t . \quad (2.6)$$

Using a Monte Carlo approach, the time dispersion was calculated for various values of h using pseudo randomly generated values of $v_y(o)$ and $v_z(o)$ reflecting the energy spectrum of electrons knocked out given by Argronovich, et al.¹⁷ The minimum time dispersion was found to be 30 psec FWHM for $h = 1.0$ mm. This value of h gives an impact energy of 300 eV on the electron detector. A study of detector efficiency showed that the efficiency reached a plateau for impact energies over 300 eV.

In conclusion, the transport system gives an energy well matched to the electron detector, giving a large efficiency with minimal time dispersion. Also, the system is imaging so that the spot size at the electron detector is the same as the foil size.

Gas Ionization and Solid State Detector Chambers

The gas ionization chamber, or AE detector, served to measure the energy loss rate of the multiply charged fragments. This, along with the E/M measurement from the time-of-flight, provided the requisite information for charge identification. Figure 2.7 illustrates the ionization chamber design. The chamber was cylindrically constructed, having an inside diameter of 16.5 cm and a total inside length of 5.1 cm. The axis of the chamber coincided with the fragment trajectories through the telescope. Thin aluminized cellulose acetate foils at either end served as the entrance and exit windows. These windows both contained the gas and provided electrically conducting surfaces contiguous with the collector and high voltage planes.

Fig. 2.7.--Drawing of Gas Ionization and Solid State Detector Chambers

The front window was mounted on an aperture 1.2 cm in diameter in the center of a brass collector plane. This plane was a disc 10.0 cm in diameter, approximately centered along the axis of the cylindrical volume and insulated from the chamber walls by a rexolite mount. A high voltage feedthrough in the top of the chamber provided the electrical connection to the collector plane.

The back window was mounted on an aperture 1.0 cm in diameter in the center of a smaller brass disc that was flush with the back wall of the chamber. This disc was 2.9 cm in diameter and served as the high voltage plane. It was electrically insulated from the back chamber wall by a rexolite ring. The high voltage was provided by a feedthrough in the solid state chamber which was connected to the back of the ionization chamber. The high voltage and collector planes were separated by a distance of 2.25 cm, although this distance was not uniform in the region between the windows, since the windows would bow out under the 16 Torr pressure that was maintained in the chamber. The high voltage plane was kept at 400 volts, so that the field sweeping out the charge deposited by the ionizing fragments was approximately 175 V/cm.

The windows were made of 10 laminations each of thin cellulose acetate foils. These were made in the following way. A drop of liquid cellulose acetate was deposited on the surface of distilled water in a Petre dish. The film on the surface of the water would harden and it could then be lifted from the water on a fine wire mesh in which holes had been punched. After further drying, a foil was lowered onto the aperture of the detector window until it broke away from the wire mesh. The foil would adhere to the lip of the aperture. Successive layers of foil were then placed on top of one another, with care being taken not to let air get trapped between the

laminations. Finally, when the last lamination had been added, the border of the foils was cemented to the lip of the aperture by dabbing it with Krylon on a cotton swab. Once this had dried the window was placed in the evacuated bell jar of an evaporator. Fine aluminum wires were electrically heated to evaporation, with a consequent deposition being made on the surface of the window.

This design choice for the ionization chamber and the final choice of heptane as the gas to be used, was made after some trials with another design and gas. These early trials were found unsatisfactory because of multiple scattering considerations in the gas volume of the chamber. The first design was a rectangular chamber 16.4 cm in length using Argon gas. The ground and high voltage planes were parallel plates on either side of the particle trajectory and parallel with that path. It was found that in this configuration the telescope acceptance was severely limited by multiple scattering. That is, the path of particles in the gas was sufficiently long so as to cause appreciable loss of charged fragments as a result of their being scattered outside of the solid angle made with the E_1 detector.

The advantages of the final design are twofold. First the path length of fragments in the gas was shortened by a factor of seven. This could be done and still retain the same signal amplitude by choosing a gas which would yield the greatest number of electron-hole pairs possible for the energy depositions of interest. High molecular weight hydrocarbons proved to be the most feasible. The choice of heptane allowed operation at pressures lower than those used with Argon, and the consequent longer radiation length helped to reduce the multiple scattering. The second advantage of this cylindrical geometry was in charge collection. Since the electric field swept the entire path of the particle in the gas, the ionization path length was unambiguous.

The gas pressure was regulated by a flow system using a capacitive manometer. The flow rate was typically on the order of $2 \text{ cm}^3/\text{sec}$, so that the gas was replenished in the chamber approximately every four minutes. It was necessary to flow the gas in order to ensure the purity of the gas which may have become contaminated from outgassing. The determination of the gas thickness in the AE chamber is discussed under the topic of calibrations in the next chapter.

The solid state detector chamber is shown in Fig. 2.7 along with the ionization chamber. The positioning of these detectors was discussed earlier in this chapter. The E_1 detector was a 100 micron transmitting semiconductor detector, the E_2 detector was a 700 micron transmitting semiconductor detector and the veto detector was a 700 micron nontransmitting semiconductor detector. Each had an active surface of 1.0 cm^2 .

Microdot feedthroughs connected the semiconductor detectors to cables of approximately 30 cm in length. These cables passed the signals on to preamplifiers that were secured to a rack mounted on the telescope housing. The high voltage feedthrough for the ionization chamber was also situated in the solid state detector chamber. This feedthrough fed directly to a preamplifier. From the preamplifiers the output signals from each of the aforementioned detectors went directly to a distribution panel before going on to the counting house.

Monitor Telescope

The monitor telescope consisted of three plastic scintillator detectors supported on a single arm at the 30° forward port of the scattering chamber on the opposite side of the beam line from the main detector telescope. Each detector was constructed of small rectangular shaped wafers of pilot-B plastic scintillator material joined to 10.0 cm long light pipes. The light pipes were cemented with transparent cement to cylindrical bases

which were themselves similarly cemented to EMI type 9813B photomultipliers. The first and third scintillators were 1.1 cm square and 0.7 cm thick, while the second scintillator was 2.2 by 1.9 cm. The first detector was approximately 24.5 cm from the target, the second detector was 24.5 cm behind the first, and the third detector was about 49.5 cm behind the second. This geometry ensured that the telescope subtended a solid angle on the target when operated in a three level coincidence mode. This was desirable since the telescope was originally conceived as a relative monitor of beam on target. However, the function of the monitor was later remanded exclusively to measuring the live-time of the data acquisition system. This was done by scaling both a bin gated and an ungated telescope coincidence, where the bin gate was open during the live-time of the system. The system live-time is discussed in the following section in the context of bin gating of the fast electronics.

Data Acquisition and Electronics

The data acquisition and electronics consist of four parts:

- (1) Fast electronics
- (2) Slow electronics
- (3) Data recording
- (4) Analysis program

Each of these subjects will be dealt with in this section except for the details of the data reduction and analysis program which will be discussed in Chapter 3.

The discussion of the fast electronics will deal with signal shaping and discrimination along with the logic employed to decide on the occurrence of an event and the readiness of the computer to process the event for recording on magnetic tape. This subsection also encompasses the scaling of

each detector and several coincidences, the generation of latches, the monitor telescope, the current monitoring toroid and the clock. Under the subject of slow logic, the analog signal processing and digitization are discussed. In addition, this subsection will deal with the gating of the system. Finally, the last subsection discusses the interfacing with the computer and the recording of the data on magnetic tape.

Fast Electronics

A schematic of the fast electronics is shown in Fig. 2.8. The primary functions of the fast logic were: (1) the generation of an event pulse that could subsequently be used to gate various input registers, (2) the generation of start and stop pulses for the time-to-amplitude converters (TAC's), (3) the generation of pulses for the scaling of various counters and intermediate logic pulses, and (4) the generation of latches.

Five signals were, or could be, used to establish the occurrence of a suitable event. These were the signals from the time-pick-off detectors, T_1 and T_2 , the solid state transmission detectors, E_1 and E_2 , and the non-transmitting, solid state detector, or veto counter, V . The ionization chamber signal, ΔE , was not used in this context.

For each of the signals mentioned above, except for the veto and ΔE , provision was made to tag events for which a signal was considered to be piled-up. No real-time event rejection was wired into the event logic, however, a latch was set on piled-up events to allow off-line rejection. This means of handling pile-up gives one a handle on the detection efficiency resulting from the pile-up rejection.

In the following, generation and use of the main logic pulses will be discussed. The time-pick-off detector signals received no preamplification, but went directly to the first stage of an amplifier in a bin mounted

Fig. 2.8.--Schematic of Fast Electronics Logic

adjacent to the experimental set-up. The DC coupled outputs were sent directly to the counting house, where these analog signals were put into analog-to-digital converter (ADC) registers. The AC coupled outputs went through the second stages of the amplifiers and then to discriminators. The discriminator logic pulses were then sent to the counting house patch panel, from which a fan-out was made. After some width adjustment of these logic pulses in discriminators a coincidence was made between the T_1 and T_2 signals, so as to yield an output signal, T. The T_1 pulse was made approximately 115 nsec wide, while the T_2 signal was made as narrow as possible, about 10 nsec. Using signals from the 5.48 MeV alpha source, which had an 18.81 nsec flight-time between the time-pick-off foils, the coincidence timing was set up such that the T_2 signal came 20 nsec inside the T_1 pulse. Hence, the timing was such that times-of-flight as long as approximately 115 nsec were allowed.

A pile-up latch was set for a given timing signal when that signal resulted in an event for which two signals were closer together than approximately 160 nsec. This was done by clipping and delaying, by slightly more than 160 nsec, a 160 nsec updating discriminator output. This clipped and delayed output and the unclipped 160 nsec pulse were put into a coincidence unit so that an output was generated only when the input had been updated by a second timing signal coming within 160 nsec of the previous pulse. This output set the latch.

Another logic signal was generated by a coincidence between T_1 and the final event pulse. This was used as the start signal for each of the two TAC's used. A delayed T_2 logic pulse was used as the stop for one of these TAC's. This TAC gave an output which was proportional in amplitude to the time-of-flight between the time-pick-off detector foils. This analog

signal was put into an input register of the PACE system where it was digitized. T_1 , T_2 and T were each scaled and used to set latches.

The analog signals from the E_1 , E_2 and V detector preamplifiers were fed directly to the counting house. Behind the patch panel signal splitters on E_1 and E_2 separated the fast and slow components of the analog signals. The fast signals were passed on for appropriate amplification, as were the slow signals. After amplification of the fast E_1 and E_2 signals they were passed through discriminators and the resulting logic pulses were fanned-out for various functions. After some pulse width adjustment a logical OR was made between E_1 and E_2 . The consequent output is hereafter referred to as the E pulse. A coincidence was also made between these two pulses, $E_1 \cdot E_2$. Scaling and setting latches were done for each of the E_1 , E_2 and $E_1 \cdot E_2$ logic pulses.

E_1 and E_2 pile-up was treated in the manner previously described, however, the electronic means of deciding upon an event being piled-up in one of these detectors was different than that employed for the timing signals. In this case conventional EG&G model GP100/NL Pile-up Gate Units were used which set latches on events for which two signals were closer together than 4 μ sec.

An E_1 logic pulse was used as a stop for the second TAC. This TAC's output, whose amplitude was proportional to the time-of-flight between the T_1 and E_1 detectors, provided another input channel into the PACE system. This information was a somewhat redundant back-up, or check, on the first TAC and was of little analytic value.

The veto signal was amplified in the counting house, and, thereafter, sent through a discriminator. Provision was made to scale and set a latch on this discriminator output.

At this intermediate stage of signal processing the following logic pulses were available to determine the occurrence of an event: T , E (E_1 or E_2), $E_1 \cdot E_2$ and V . A coincidence between T and E was made, and its output scaled and latched. Then a logical OR was made between this $T \cdot E$ and the $E_1 \cdot E_2$ signal. The subsequent signal was placed in anticoincidence with the signal, V , resulting in the event signal, EVT . Production data were taken in a much simplified mode. The E_2 input into the E_1 OR E_2 was disabled, as was the $E_1 \cdot E_2$ input into the unit generating the event pulse. So, an event during data collection was a coincidence between T_1 , T_2 and E_1 in the absence of a veto registration. Hence, the veto served to reject events where the particle was energetic enough to penetrate beyond the E_2 detector. This gave the upper limit on the energies of the various fragments detected in the telescope.

The logic described above was readily adaptable to special studies. Data for efficiency studies of the T_1 and T_2 detectors were taken by making the T signal into a logical OR (T_1 or T_2), and then doing a coincidence with E_1 as before.

The EVT pulse was fanned-out for a number of different purposes, most of which were gating. Gates generated from the EVT included those for the latches, the T_1 and T_2 ADC's, the PACE event gate, the gate for the linear gates used in the slow electronics, and the event bin gate.

Most of the fast electronics was bin gated, the bin being disabled after each event for a period of 250 μsec to allow the computer to process the event. This gating leads to a system, or computer, dead-time. The primary function of the monitor telescope was to account for this system dead-time. Nominally, a three level coincidence was made with the signals from the monitor scintillator detectors, however, a two level coincidence between the second and third counters usually proved better for the count rates we

had. This coincidence was not bin gated, but the output was put through a second unit of binning. The ratio of the scalar counts from these bin gated and ungated monitor coincidence units gave the fraction of the time the system was unresponsive.

Two other scalars of note are the clock and the toroid. The clock was a pulser whose output was put in coincidence with the run gate. That is, so long as a run was in progress, the pulser, which was set at a repetition rate of 1 kHz, was being scaled. Similarly, the toroid, which monitored the beam current, scaled in proportion to that current, and only when enabled by the run gate.

Slow Electronics

The slow electronics, shown in Fig. 2.9, encompasses much of the analog signal processing. The T_1 and T_2 analog signal processing has already been discussed, as has the generation of the time-of-flight analog signal, T . Both the E_1 and E_2 slow signals from the signal splitters mentioned above were amplified. The monopolar outputs with base line restoration were each put into linear gates. The ΔE signal came directly to the counting house from the preamplifier and went into an amplifier. The amplified signal went to a linear gate. The linear gates were each gated by a 2.75 μ sec wide gate generated from EVT pulse of the fast logic. These linear gates provided noise suppression and an adjustable pedestal for the analog signals. The outputs from the linear gates went to PACE Stretcher Multiplexer units, so that the PACE system now had five input channels; the two time-of-flight signals, in addition to the E_1, E_2 and ΔE . During the production run on the 30° angle the second time-of-flight measurement was disabled from PACE, and so, this backup was not available.

The PACE system is a multiparameter analog-to-digital converter. Three types of modules make up the system, the stretcher multiplexers, the multiplexer controller, and the analog-to-digital converter. Each input channel goes into a stretcher multiplexer. These units are peak sampling devices. Once an input signal crosses a threshold the unit will become disabled after the slope of the input pulse goes to zero. The voltage at this point will be stored until the multiplexer controller queries the unit. At this point a current pulse proportional to the stored voltage is sent to the analog-to-digital converter for digitization. After each channel has been read out the system can be readied to receive the analog signals of another event.

The LAMPF gate generator was used, in parallel with the enabling and various file initializing and ending capabilities of a unit known as the "Green Lizard," to maintain overall control of the data acquisition system. This unit scaled the events and compared this with the preset number of events chosen for that given run. Figure 2.10 shows a schematic of the gate generator logic. The prime function was to generate the bin gate for the fast electronics. This gate resulted from a three level coincidence between the beam gate, the run enable and the run gate. The beam gate was on during the 500 μ sec macropulse in the macrostructure of the beam time profile. This reflected the 6% duty factor of the accelerator which gave 120 macropulses per second. The run enable came from the Green Lizard described below. This signal indicated that the computer was ready to accept the next event. Finally, the run gate indicated that a run had been started. The run gate was terminated either manually by stopping the run or automatically when the scalar reached the predetermined count for the run. Additionally, the LAMPF gate generator was used to make a coincidence between the beam gate and the

Fig. 2.9.--Schematic of Slow Electronics

Fig. 2.10.--Schematic of Gate Generator Logic

run gate. The barred output was then put into the VETO input of the monitor telescope coincidence unit. This constrained the monitor telescope only to count during a run and within the macropulses of the beam.

Computer and Data Recording

Beyond the event logic, analog signal processing, gating, and the generation of pulses for scalars and latches, was the reading of the consequent data and writing it on magnetic tape. In addition, provision was made for a semi-on-line analysis to be performed by the system PDP-11/20 computer. The aforementioned scalars, latches and ADC's were all CAMAC modules. Also, the output from the PACE system went to another CAMAC module, the PACE interface module. The CAMAC system served to transmit data between the instrumentation modules and a digital controller or computer. The computer servicing CAMAC and controlling the tape writing and data flow for the semi-on-line analysis was the MBD, or Microprogrammed Branch Driver. The function of the MBD was to read event data from the CAMAC system, buffer this data and, on attaining a full buffer, to write a record on magnetic tape. The event data consisted of forty-eight words each and ten events were contained in each record. A schematic of the system configuration is shown in Fig. 2.11. The data was written on tape by means of a Berkeley controller with an IBM 729 tape drive. Control of the MBD program was exercised via the Green Lizard, which connected to a kinetics systems 3420 CAMAC input module. These units, in addition to transmitting the event data, also provided information to the MBD instructing it on initialization of runs and writing end-of-file marks on tape.

The PDP-11/20 computer was used for loading and controlling the MBD. Additionally, the main analysis code was available on this computer for a semi-on-line look at the data. A Tektronix 4010 scope was used to display

Fig. 2.11.--Schematic of Data Acquisition System

various diagnostic histograms and scatter plots at the end of runs. Histograms of the T_1 and T_2 ADC outputs and the outputs from the various detectors measuring energy depositions would indicate the suitability of the amplifier gains and the correct operation of the digitization units. Mass and charge histograms would point broadly to the deterioration of some critical resolution. There was no capability to see these plots in real-time, but periodic checks were valuable and time saving.

Another useful display could be made on a television monitor of various digital CAMAC outputs. This permitted one to display in real-time the scalars and ADC's, which proved valuable for diagnosing problems and checking on the operation of the system.

CHAPTER 3

DATA REDUCTION AND ANALYSIS

Introduction

The reading of the data tapes and subsequent data processing to the point of generating raw, unnormalized spectra were performed on an off-line PDP 11/45 computer with a computer code designated EX179. Other supporting computer codes were run on an IBM 6600. These included codes to generate or modify stopping power tables, a Monte-Carlo acceptance code for the detector telescope, and efficiency correction codes for the time-pick-off detectors. Discussion of the main analysis code, the spectral corrections resulting from the telescope acceptance and efficiency, resolutions, absolute normalization of the production cross sections and calibration of the various detectors follow. The results and their interpretation are given in Chapter 5.

The first function of the analysis code EX179 was to read each event from magnetic tape and decode the data. For each event the following information was recorded: run number, target, scattering chamber port angle, gas ionization chamber pressure, all scaler and latch values, and the ADC and PACE digital outputs. The PACE output had a range of 8192 channels and the ADC's gave their output over a range of 250 channels. The energy and time information was digitized by PACE and the ADC's handled the amplitudes of the time-pick-off signals.

Each telescope detector was scaled continuously between events, along with the coincidences $T_1 \cdot T_2$, $T \cdot E$, $E_1 \cdot E_2$ and the monitor telescope

coincidences M and M_G . Each of these except M was bin gated and, therefore, scaled only during the live-time of the system. Additionally, the clock and toroid signals were scaled between events and were ungated. The scalers were each set back to zero after each event. A summary accompanying all analysis jobs gave, for each scalar, the scalar totals of all the events processed and a table of scalar ratios showing the ratio of counts for each scalar to the counts in M_G . Latches were used to indicate whether or not a given logic pulse was present for the event. The latch totals for each job were also displayed. Finally, the summary contained the total counts for various failure flags which had been set when anomolous events occurred. These flags will be explained below.

The first step in the analysis, was to convert the raw digital information to numerical values in standard units and determine the completeness of the data for each event. This involved subtraction of pedestals and multiplication by gains determined in the calibration of the detectors. Thus ΔE , E_1 , and E_2 were known in MeV, T was known in nanoseconds, and the T_1 and T_2 ADC signals were known in terms of their 250 channels. An event with a pulse height falling below a predetermined threshold had a flag set so as to allow discrimination in the analysis.

Although most data were collected with the event trigger being a coincidence between the T_1 , T_2 , and E_1 detectors, the analysis code made provision to process events with various combinations of data from different detectors. This provided flexibility in the event logic one could choose. The minimum requirements for a complete particle identification were an adequate signal for the time-of-flight, T , and adequate energy loss rate signal, ΔE , and total energy, E .

Particle Identification

The particle mass identification, A , necessitated two pieces of data, the energy per atomic mass unit, E/M , and the total energy, E . The first of these could be determined from the time-of-flight over the known flight path of 30.5 centimeters. Since this gave a measure of the particle velocity, the non-relativistic equation used was

$$E/M = v^2/2 .$$

In order to achieve the maximum intrinsic resolution in the time-of-flight (TOF) measurement, corrections had to be made to account for time slewing. That is, one would like to correct for the differences in rise times of the leading edge of pulses of different amplitude coming from the time-pick-off detectors. The leading edge of a time-pick-off pulse was approximated by the functional relationship $A = A_0 T^q$. This is illustrated in Fig. 3.1. For a discriminator trigger set at V_D , the time between the initiation of the analog signal and the subsequent trigger of the discriminator when its threshold is reached is given by

$$\tau = \left(\frac{V_D}{A_0}\right)^{1/q} = (V_D)^{1/q} (A_0)^{-1/q} . \quad (3.1)$$

For simplicity, the following substitutions were made $Q = -1/q$, $T_k = A_0$, and $B_k = V_D^{1/q}$, where k is 1 or 2 and represents the start or stop signal. The corrected TOF, T_c , was then written in terms of the uncorrected TOF, T , the T_1 and T_2 amplitudes, and the Q and B parameters as

$$T_c = T - B_1 T_1^Q + B_2 T_2^Q$$

Additionally, the cable delays to the start and stop of the time-to-amplitude converter (TAC) gave rise to a timing pedestal, T_0 , which had to be accounted

Fig. 3.1.--Approximation for Leading Edge of Time-Pick-Off Detector Pulses. V_D is the discriminator threshold and τ is the rise time to the threshold.

for. The delay to the stop was longer than to the start, therefore,

$$T_c = T - T_o - B_1 T_1^Q + B_2 T_2^Q . \quad (3.2)$$

The slewing parameters, B_1 and B_2 , are related to the discriminator trigger levels, and T_1 and T_2 are the signal amplitudes from the ADC's. Typically, Q was chosen to be -0.5 , which assumed that the leading edge of the timing pulses could be simulated by a quadratic. The slewing parameters had to be determined empirically.

The slewing parameters were found by analyzing data from a mono-energetic alpha calibration source. From Eq. (3.2), one expected that, if there were no slewing, and B_1 was set equal to zero, T_c would be independent of T_1^Q . In order to remove any dependence, a scatter plot was made of $T - T_o + B_2 T_2^Q$ versus T_1^Q . $T - T_o + B_2 T_2^Q$ was provided by the computer by calculating T_c with $B_1 = 0$. A line drawn through the maxima of this scatter of points would be horizontal if, in fact, there were no dependence on T_1^Q . Any dependence on T_1^Q provided a value of B_1 (the slope of the line) which, when included in Eq. (3.2), removed the dependence of T_c on T_1^Q . Similarly, with B_2 the slope of the T_c versus T_2^Q scatter plot with B_2 equal to zero, gave a measure of the amplitude to be assigned B_2 .

The extension of the line drawn through the scatter of points ought to intercept the T_c -axis at a value corresponding to the time-of-flight of the alpha particles. Adjustment of T_o insured agreement with a calculated TOF by setting

$$T_c \text{ (nsec)} = X \sqrt{\frac{M_\alpha (931.478)}{2E}} / 29.979 , \quad (3.3)$$

where X is the path length in centimeters, M_α is the alpha mass in atomic mass units, and E is the alpha energy in MeV after having passed through the first time-pick-off foil.

With the corrected TOF, it is straightforward to determine E/M,

$$E/M = \beta^2/2 (931.478) ,$$

where

$$\beta = X/T_c (29.979) .$$

The determination of the total energy involved summing the energies deposited in each detector and making some adjustment for the deadlayers through which the particle passed. Deadlayers were regions of stopping material through which a charged particle passed, losing energy which was not registered in any detector. The bulk of the events of interest penetrated no further than the E_1 detector. For these events it was first thought that the deadlayer correction could be made by assuming that the stopping power, dE/dx , remained nearly constant as the particle transversed the deadlayers and the ionization chamber. The thickness of each layer was expressed as an equivalent thickness of aluminum. The stopping power was determined from the energy loss in ionization chamber using the following relationship

$$\frac{1}{\rho} \frac{dE}{dx} = \frac{\Delta E}{\Delta x_G (\text{mg/cm}^2)}_{Al} , \quad (3.4)$$

where dE/dx is the energy loss rate in aluminum, ρ is the density of aluminum, ΔE is the energy loss in the ionization chamber, and Δx_G is the equivalent thickness of the ionization chamber gas in terms of milligrams per square centimeter of aluminum. Taking η_1 as the sum of the thicknesses of the deadlayers and the gas ionization chamber sensitive volume, the energy can be expressed as

$$E = \eta_1 \left(\frac{\Delta E}{\Delta x_G} \right) + F_1 . \quad (3.5)$$

Figure 3.2 is a schematic of the telescope deadlayers from which one can see that

$$\eta_1 = T_2 + W_1 + \Delta x_G + W_2 + Au(E_1) , \quad (3.6)$$

where T_2 is the second time-pick-off foil, W_1 and W_2 are the front and back windows on the ionization chamber, Δx_G is the gas, and $Au(E_1)$ is the gold surface on the front of the E_1 silicon detector. With a slight rearrangement,

$$E = \left(\frac{\eta_1}{\Delta x_G} \right) \Delta E + E_1 . \quad (3.7)$$

It can be seen that the magnitude of the correction for deadlayers is determined by the ratio of the sum of deadlayers plus gas thickness to the gas thickness.

This method of correcting for deadlayers proved inadequate because at low particle velocities the stopping power curve changes too rapidly as a function of energy. The variations in the stopping power during the traversal of the deadlayers and the ΔE detector gas was observed to cause hooks in scatter plots of atomic mass (A) versus the energy per unit mass (E/M). These scatter plots should have given horizontal bands, one band for each mass. However, at values of E/M less than approximately 0.4 MeV per atomic mass unit there were upward hooks in the plots. Since atomic mass was calculated by dividing the particle energy by the value of E/M , either E was being determined too large or E/M too small in this region. It was established that the assumption of a constant stopping power throughout this region was the source of an overestimation of E . To compensate, the ratio $\eta_1/\Delta x_G$ was made a function of E/M in the region where the deviation occurred. This functional relationship was determined empirically from the hooks in the data, and the resulting fixup yielded the desired uniform mass identification. The adjustment of the ratio $\eta_1/\Delta x_G$ varied according to the particle charge,

Fig. 3.2.--Schematic Diagram of the Telescope Deadlayers

Z, as well. Here again, the shape of the stopping power curve in this region of low velocity was the cause of the problem. The A versus E/M scatter plots served as a useful diagnostic tool in the analysis, as the desired horizontal bands would be a consistency check on the total energy and E/M calculations.

A smaller fraction of events penetrated through the telescope to give an E_2 registration. In this case the deadlayers were treated in the same manner as described above except that two new deadlayer regions were added,

$$\eta_2 = T_2 + W_1 + \Delta x_G + W_2 + Au(E_1) + Al(E_1) + Au(E_2) . \quad (3.8)$$

The new deadlayer $Al(E_1)$ was the aluminum backing on the E_1 silicon detector and $Au(E_2)$ was the gold facing on the front of the E_2 detector. The total energy for these events was then

$$E = \eta_2 \left(\frac{\Delta E}{\Delta x_G} \right) + E_1 + E_2 . \quad (3.9)$$

These particles, being of higher velocity than those not penetrating the E_1 detector entirely, lost a smaller fraction of their total energy in the deadlayers and the slope of the stopping power curve was more nearly constant. Hence, the deadlayer correction was adequate, without the need of making the ratio $\eta_2/\Delta x_G$ a function of E/M.

Other events could arise with the logic employed. That is, a lightly ionizing fragment could have failed to yield an adequate ΔE signal, yet have given an E_1 signal, or E_1 and E_2 signals. Events of the first kind were unlikely since particles so lightly ionizing as to fail to register in the ΔE counter were going to penetrate beyond the E_1 counter. Flags were set on such events, if they occurred, so that they could be looked at apart from the bulk of the data. Events of the second kind were possible, and the

total energy calculation was done in the same manner as elucidated above except that now

$$\frac{1}{\rho} \frac{dE}{dx} = \frac{E_1}{\Delta x_{E_2}} (\text{mg/cm}^2)_{\text{Al}} \quad (3.10)$$

so that

$$E = \eta_2 \left(\frac{E_1}{\Delta x_{E_1}} \right) + E_1 + E_2 \quad (3.11)$$

Here, Δx_{E_1} is the equivalent thickness of the E_1 detector sensitive volume in milligrams per square centimeters of aluminum. E_1 served as the incremental energy loss in the same way that ΔE had in the preponderance of events. These events were rare and, again, a flag on the event indicated the anomalous lack of ΔE data.

The fragment charge identification was done in the analysis code from the E/M and ΔE data. Tables of stopping power were stored in memory for each particle mass. Once the mass identification was completed in the manner described above, a routine was called to determine the particle charge by interpolating the E/M, ΔE data point between the family of curves arising for the various atomic charges with this given mass. The look-up tables had a range in E/M of from 0.20 to 8.00 MeV per nucleon, and extrapolations beyond these bounds were not made. The tables were also restricted to atomic masses no greater than 22 atomic mass units. This restriction was near the limit of the telescope mass resolution.

A useful diagnostic tool in the analysis was a scatter plot of charge, Z, versus E/M. The charge identification should be independent of E/M, and so, these scatter plots ought to have given horizontal bands, one band for each atomic charge. At low values of E/M, however, there were deviations. As E/M became smaller the Z identification became too large,

resulting in an upward hook in these scatter plots at low velocities. The hooking became more severe for the more highly charged ions. From these plots, and Z versus ΔE scatter plots, it was clear that for a given Z the low velocity fragments, and hence those having the greatest energy loss in the ΔE , were being assigned to a large value of charge. The source of the problem was identified as originating from the stopping powers used to generate the look-up tables. These tables had been generated from range tables for the various ions of interest in heptane gas. The range tables came from integrating heptane stopping power tables that had themselves been derived from the stopping powers of the elemental constituents of heptane, properly weighted. These elemental stopping powers came from the tables of Northcliffe and Schilling for heavy ions.¹⁸ Unfortunately, the carbon stopping powers reported by Northcliffe and Schilling were for solid, elemental carbon, whereas, the application was being made to a gaseous hydrocarbon. There are numerous articles reporting on the effects of physical and chemical state on stopping power and on the deviation of hydrocarbon stopping powers from those expected when merely using the available elemental data.¹⁹⁻²⁸

The most direct way to improve the charge identification was to generate stopping power tables from the data itself. This permitted extraction of the full charge resolution of the system. Figure 3.3 shows a scatter plot of ΔE versus E/M . The quality of the intrinsic charge resolution shown in the plot was better than that displayed in a charge histogram. It can be seen that the family of curves made up from the various ion charges are clearly resolved for all atomic numbers down to values of E/M around 0.25 MeV per nucleon. A computer code was written to take data from these scatter plots, smooth this raw data and provide for interpolation to determine

Fig. 3.3.--Scatter Plot of ΔE Versus E/M

values of $\Delta E/Z^2$ at an arbitrary E/M. The code then would calculate dE/dx and integrate the reciprocal to give energy-range tables for a common isotope of each atomic charge. These range tables then served as input to a second computer code that generated the look-up tables used in the data analysis. This proved successful in removing the hooks in the Z versus E/M scatter plots, and gave the optimal charge resolution. An expanded discussion of the method used to generate the new stopping power tables from the ΔE versus E/M scatter plots is given in Appendix A.

Of considerable analytic value was one other variable calculated by the analysis code. T_z was the difference between the experimentally measured fragment time-of-flight and the time-of-flight expected for the same particle of mass m_0 with the experimental measured energy E,

$$T_z = T_{\text{measured}} - T_{\text{theoretical}} = T_c - X \sqrt{\frac{m_0 (931.478)}{2E(\text{MeV})}} / 29.979 \quad (3.12)$$

The above expression gives T_z in nanoseconds when the flight path, X, is given in centimeters. The value of T_z is largely that of a consistency check rather than as a specific diagnostic tool or as a tool for tuning up the various calibrations, though it was helpful in these latter endeavors as well. If, for a given mass, T_z was very nearly zero over the entire range of energies, then one could be fairly certain that all of the empirically determined parameters established in the calibrations were correct. That is, the pedestals and gains for the time-of-flight measurement gave results which were consistent with the energy calculation, which encompassed the pedestals and gains of each of the energy detectors and the deadlayer corrections. Fundamentally, T_z measured the magnitude of inconsistency between the E/M and E calculations. Hence, the T_z resolution was closely linked to the mass resolution of the telescope.

The following discussion illustrates how T_z was used as a consistency check. Equation (3.12) can be written out with T explicitly written as a function of E/M ,

$$T_z = \frac{X}{c} \frac{1}{\sqrt{2(E/M)}} - \frac{X}{c} \sqrt{\frac{m_0}{2E}}. \quad (3.13)$$

Here, c is the speed of light. Rearranging this equation

$$T_z = \frac{1}{\sqrt{2}} \frac{X}{c} (\sqrt{M} - \sqrt{m_0}) \frac{1}{\sqrt{E}}. \quad (3.14)$$

A scatter plot of T_z versus $1/\sqrt{E}$ should exhibit a grouping of data points along a horizontal line for all events with $M = m_0$. For events with M greater than, or less than m_0 the grouping of data points will be along lines with positive or negative slopes respectively. This family of straight lines should extrapolate to $T_z = 0$ as $1/\sqrt{E}$ goes to zero. Deviations of these lines from straight reflected inconsistencies and pointed broadly to the problem area.

Resolutions

The mass resolution of the counter telescope depended upon the energy resolution of the detector array and the time resolution of the time-of-flight measurement in the following way,

$$\left(\frac{\delta M}{M}\right)^2 = \left(\frac{\delta E}{E}\right)^2 + \left(2 \frac{\delta t}{t}\right)^2. \quad (3.15)$$

The intrinsic resolution of the detectors was determined using the monoenergetic alpha calibration source of 5.48 MeV. These alphas had been degraded in energy by deadlayers to 5.35 MeV before entering the AE ionization chamber sensitive volume. At a gas pressure of 16 Torr the alphas deposited 193 keV within this volume. The full-width-at-half-maximum (FWHM) of the peak was 35 keV. This same alpha source deposited 5.05 MeV in the

E_1 silicon detector with the nominal gas pressure in the ΔE chamber. The FWHM of this peak was 45 keV. The resultant total energy peak, which reflected each of these detectors and the deadlayer correction, had a FWHM of 65 keV. Consequently, for $\delta E/E$ one gets 0.012. Figures 3.4 through 3.6 show the energy resolutions of the individual detectors as well as the total energy resolution.

The optimal time resolution of the telescope was on the order of 250 psec for the alpha source flight-time of 18.81 nanoseconds. This is illustrated in Fig. 3.7. Hence, the time resolution ($\delta t/t$) was 0.013, which gave a theoretical mass resolution of $\delta M/M = 0.029$. Figure 3.8 shows a ^4He histogram of data taken from an aluminum target having a FWHM of 0.20. This gives a mass resolution of $\delta M/M = 0.05$. As an illustration of the clean mass separation achieved, Fig. 3.9 shows a histogram of mass six and seven fragments in the range of E/M of 0.50 to 0.75 MeV per nucleon. The mass resolution achieved was thought to be adequate to the investigation of the production cross sections of all the isotopes up through those of oxygen.

The atomic charge identification scheme described in the last section indicated that the charge resolution was dominated by the resolution of the ΔE detector. Figure 3.10 is a Z-histogram of helium-4 and it shows a FWHM of about 0.14. This gives a $\delta Z/Z$ of 0.07. The clean separation of atomic numbers three and four is shown in Fig. 3.11, which is a Z-histogram of atomic mass seven events.

These resolutions are those achieved from the best quality data. A small fraction of the data at the 30° forward angle was of lesser quality, and so, the resolutions, especially the mass resolutions, were poorer. The deterioration arose in the time-of-flight measurement due to some unidentified instability which caused the time measurement to drift slightly during a run.

Fig. 3.4.--Histogram of ΔE from the 5.48 MeV Alpha Calibration Source

Fig. 3.5.--Histogram of E_1 from the 5.48 MeV Alpha Calibration Source

Fig. 3.6.--Histogram of E from the 5.48 MeV Alpha Calibration Source

Fig. 3.7.--Histogram of the Time-of-Flight Measurement from the 5.48 MeV Alpha Calibration Source

Fig. 3.8.--Mass Histogram for Z = 2 Particles

Fig. 3.9.--Mass Histogram of Mass Six and Mass Seven Fragments

Fig. 3.10.--Charge Histogram of Helium Fragments

Fig. 3.11.--Charge Histogram of Charge Three and Charge Four Fragments

Calibrations

This section deals with the calibration of the time-of-flight measurement and the various energy detectors, as well as the determination of dead-layers and target thicknesses. As described earlier, the processing of the digital information that came from the analog signals involved the subtraction of pedestals and multiplication by gains which converted PACE channels into convenient units, such as nanoseconds for time and MeV for energy measurements. An Americium-241 alpha source was used in all calibrations mounted either in the scattering chamber as described in Chapter 2, or at the back of the time-of-flight chamber facing back toward the ΔE chamber. The alpha source in the scattering chamber was present at all times, and so gave a continuous fiducial point in the data.

The pedestal and gain for the time-of-flight, T , measurement was done by taking data points for the mean PACE channel with varying delays of known amount to the start and stop of the time-to-amplitude converter (TAC). A least-squares-fit of the data would yield a gain in terms of nanoseconds per PACE channel. The pedestal was arbitrary in this case since it was effectively redundant on T_0 . However, a pedestal could be assigned once the delays to the TAC start and stop were established by comparing the mean PACE channel of T with the 18.81 nsec flight time of the alpha source.

The E_1 and E_2 detectors were usually calibrated before a run by using an alpha source mounted in the time-of-flight chamber with no gas or windows in the ionization chamber. First the E_2 detector was mounted and calibrated, and then the E_1 detector. A precision pulser was used to send test pulses to the detector preamplifier which gave back signals of equal amplitude to those of the alpha source. This effectively calibrated the pulser so that one could dial a test signal which would give a charge

deposition in the preamplifier equivalent to that given by some known energy deposition in the detector. With this capability one could get data correlating energy deposition with the mean PACE channel for that detector. A least-squares fit then gave the gain and pedestal.

E_1 was typically calibrated on a multichannel analyzer as well in order to facilitate deadlayer determinations. Without removing the alpha source used in the E_1 calibration, each of the ionization chamber windows were mounted and the consequent energy degradation of the alpha particles was measured by E_1 . From stopping power tables the window thicknesses could then be calculated. The gold and aluminum deadlayers on the front and back of each silicon detector were those given by the manufacturer.

With the deadlayers and the E_1 calibration it was then possible to calibrate the ionization chamber. The difference in energy depositions in E_1 with gas in and gas out of the ΔE detector gave a measure of the energy lost by the alphas in the gas sensitive volume. As with the E_1 calibration, the precision pulser could be matched with the alpha ΔE analog signal and subsequently used to calculate the pedestal and gain in the same manner as had been done with E_1 .

Determining the thicknesses of each of the targets was done simply by taking alpha spectra from the calibration source outside of the beam gate with the target in place. The energy degradation of the source in the target, along with the orientation of the target to the axis of the telescope, gave a measure of the target thickness. For the data collected at 90° , the normal to the target was set at 30° counterclockwise to the downstream beam direction. The data at 30° was collected with the normal at 30° clockwise to the beam.

Telescope Acceptance

In order to normalize the energy spectra, one must account for any discrimination the detector telescope made against particular species of fragments and/or energies of a given species. Two phenomena contributed to this kind of preferential acceptance of the telescope for different fragments, these being, multiple scattering and perturbation of the ion trajectories by the magnetic fields of the time-pick-off detectors. The circular aperture of the E_1 detector defined the solid angle of the telescope with the beam spot. However, with stopping material and regions of magnetic field intervening between the beam spot and the defining aperture, not every charged ion fragment which emerged from the target within this solid angle made it through the telescope. The straight line trajectories were perturbed both by multiple scattering in the stopping material and the magnetic fields. Additionally, by these same mechanisms, some fragments were scattered or deflected into the solid angle which were initially outside. The telescope acceptance reflected the relative abundances of ions of a given species and energy traversing the length of the telescope with and without the intervening stopping material and magnetic fields. The acceptance served as a correction factor to the raw spectra.

A description of the Monte Carlo computer code written to calculate the telescope acceptance as a function of energy, fragment charge state and atomic mass follows. The source of particles generated by the Monte Carlo code must be representative of the beam spot and the state of the fragments emerging from the target. The beam spot was represented as being gaussian in both the vertical and horizontal directions, with specified standard deviations.

At the particle velocities measured, the ions were not fully stripped when they emerged from the target. On passing through a solid medium an ion

will be stripped of electrons and will pick up, or capture, electrons at rates that are predominately a function of the ion velocity. An equilibrium is reached in these charge-changing cross sections after passage through on the order of $1 \mu\text{g}/\text{cm}^2$ of material.¹⁹ Each of the targets was of sufficient thickness that charge equilibrium could be assumed for ensembles of product ions emerging from the bulk of the target. A very small fraction of fragments from interactions in the back of the target material might not have reached equilibrium. The manner of choosing charge state distributions is now discussed.

The mean charge of an ensemble of ions which had reached a state of equilibrium was calculated and the width of the charge distribution for a given velocity was determined. The best semiempirical relationship for the mean charge, $\bar{Z}$, for $Z \leq 10$ is given by Dmitriev and Nikolaev²⁹

$$\bar{Z}/Z = \log(v/m_1 Z^{\alpha_1}) / \log(n_1 Z^{\alpha_2}) \quad (0.3 \leq \bar{Z}/Z \leq 0.9) \quad (3.16)$$

where, for a solid stripper, $\alpha_1 = 0.1$, $\alpha_2 = 0.6$, $m_1 = 1.2$, $n_1 = 5.0$ and v is the velocity in units of 10^8 cm/s. In a more recent article³⁰ these same authors gave an expression for the distribution width for solid strippers to be

$$d = \{\bar{Z} [1 - (\bar{Z}/Z)^{5/3}]\}^{1/2} . \quad (3.17)$$

The first of these relationships, Eq. (3.16), has the problem that it is restricted in range of application to $0.3 \leq \bar{Z}/Z \leq 0.9$. Figure 3.12 shows that the following equation gives close agreement with this first equation and is not so restricted,

$$\bar{Z}/Z = (1 - e^{-125\beta/Z^{2/3}}) . \quad (3.18)$$

Fig. 3.12.--Comparison of Eqs. (3.16) and (3.18) for the Mean Charge States of Ions

Agreement between the two expressions for the ratio $\bar{Z}/Z$ in the range of validity of Eq. (3.16) is within 5%. Hence, this last equation for $\bar{Z}$ and the distribution width relationship were used to generate the charge states of the fragments emerging from the target.

Having generated the spacial position and the charge states of ions emerging from the target, the next task was to randomly throw the initial components of the particle's momentum vectors. Given the small solid angle made by the telescope entrance aperture with the source, it was assumed that this aperture was uniformly illuminated by particles from the source. That is, the particle flux was taken to be constant across the aperture. The entrance aperture itself had to be chosen in such a way as to include all possible ion paths which would give a registration in the last detector, which defined the solid angle for the telescope. This aperture was chosen to precede the first region in the telescope which could perturb the ion paths from their initial direction, and it was made large enough to allow all paths of interest.

The entrance aperture could be uniformly illuminated from a point source in the following way. Let ψ be the half-angle made between the axis of the telescope and a line from the source to the circumference of the aperture. The telescope axis is taken as the Z-axis. Then, in cylindrical coordinates, one can generate rays with direction angles θ and ϕ which uniformly illuminate the aperture if

$$\cos\theta = (1 - \cos\psi)/(1 - \cos\psi - \xi) \quad (3.19)$$

and

$$\phi = 2\pi\xi, \quad (3.20)$$

where ξ represents randomly generated numbers between 0 and 1. Given these direction angles for the momentum vector, the coordinates of the vector in momentum-space could be easily found. To retain the uniform illumination from a distributed beam spot source the initial momentum vectors had to be adjusted for particles generated off the axis of the telescope. In the same manner described above, an aperture of the same dimension, but displaced from the telescope axis by the same amount and direction as the particle origin was from the axis, was uniformly illuminated. The momentum vectors were then rotated back toward the axis of the telescope by an angle equal to the displacement angle of the particle off axis. This displacement angle was defined by the particle position in the spot, the center of the entrance aperture, and the center of the beam spot.

The acceptance code models the detector telescope with four kinds of components: drift regions, thin foil multiple scattering regions, extended multiple scattering regions and regions with uniform magnetic fields. The drift region simply transports the fragment in a linear path through the length of this component of the telescope. The momentum vector is unaltered, but the spacial coordinates change according to the translation of the particle as it moves through the region. Both the length of the region and the diameter of the aperture defining the exit from the drift region are specified. At the end of the drift a test is made to check that the particle is inside the circumference of the exit aperture.

Thin foils and extended multiple scattering regions are treated similarly, the difference being that the extended region can be sliced up into individual slabs, each being treated separately as a region of multiple scattering. In each foil or slab of scattering material the root-mean-square multiple scattering angle is calculated using the formula

$$\frac{Z' e^2}{4 \pi \epsilon_0 m v^2} \quad (3.17)$$

where $Z' e^2 / 4 \pi \epsilon_0 m v^2$ is the effective, or mean, charge of the particle, E is the energy per atomic mass unit, x is the thickness of the foil or slab, and λ_e is the radiation length of the particle in the scattering medium. The effective charge was calculated using Eq. (3.18). The scattering angles of the ions were generated so as to have a gaussian distribution with the above root-mean-square values. The new components of the momentum vector were then calculated and an energy loss routine determined the energy dropped in the foil or slab. The new spatial coordinates were determined at the end of the region and a test was made to determine whether the fragment was within the exit aperture of this telescope component. The telescope foils included the carbon foils and the windows on the ionization chamber. The gas volume of the ionization chamber was the one extended region of multiple scattering.

The perturbation of the ion trajectories by the magnetic fields of the time-pick-off detectors was treated as follows. The effective length (L) and magnetic field strength (B) of a region was determined by mapping the magnetic fields along the fragment trajectory through the pole faces of the detector magnets. These values were used to calculate the spacial displacement, D , of the ion passing through the field region,

$$D = .0347 \left(\frac{Z'}{M} \right) \frac{BL^2}{(E/M)} \quad (3.22)$$

In this equation D is in cm if B is given in tesla, L is in cm, M is in a.m.u., and E/M is in MeV/a.m.u. The ion charge, Z' , is the charge state generated in the manner discussed above, and reflects a charge distribution characteristic of the ion velocity. The change in the momentum vector resulting from the magnetic force was calculated from the translational velocity imparted to the ion in passing through the field,

with $\mathbf{r}_i = \mathbf{r}_j = \mathbf{r}$.

Summarizing, the Monte Carlo code generated ions emerging from the target with phase-space distributions representative of the beam spot and with finite probabilities of being accepted by the telescope. The charge distribution of the ions was that expected from an equilibrium condition in the target during core fission as the ions traversed the target and emerged. The fragments were transmitted through the successive telescope components until their trajectories were either perturbed outside the acceptance of the next aperture or they successfully traversed the length of the telescope. For a point source on the axis of the telescope the acceptance would simply be the ratio of fragments making it through the telescope to the number of fragments thrown into the solid angle of the last detector. For a distributed source, a weighting had to be given successful events for which the origin of the fragment in the target was far enough from the telescope axis that part of the last detector was obscured by the entrance aperture. This effectively cut down the solid angle of the telescope for these events. The weighting of events was done by calculating a geometry factor, G , for each event. This gave the ratio of the solid angle available to the event with the last detector, Ω_2 , to the solid angle into which particles were being thrown, Ω_1 . This ratio was effectively the probability of a particle, being thrown in the manner described above, traversing the telescope with no intervening regions where the ion trajectories could be perturbed. Calculation of the acceptance, A , then proceeded by summing the weighted successful events and dividing by the number of fragments generated, N ,

$$A = \frac{1}{n} \sum_{i=1}^n \frac{C_{i1}^2}{C_{i1}^2 + C_{i2}^2 + C_{i3}^2} \quad (3.13)$$

Here, n is the total number of fragments successfully traversing the telescope.

Figure 3.13 through 3.19 show the calculated telescope acceptance as a function of E/M for each of the ion species for which differential cross sections were generated. For a given value of E/M , the magnitude of the multiple scattering angle was a function of the ratio of effective charge to mass. Hence, as expected, the acceptance is poorer for ions such as ^3He compared with ^6Li .

The nominal beam spot size was taken to have standard deviations in the horizontal and vertical profile of .382 and .106 cm respectively. The acceptance was found to be fairly insensitive to the spot size as is shown in Fig. 3.13 where points are plotted of the acceptance of ^4He with one-half and one-and-one-half times the nominal spot size. Nowhere does the acceptance change by much more than 10% with these smaller or larger beam spots.

Figure 3.13 also shows the ^4He acceptance with the magnetic fields of the time-pick-off detectors turned off. This shows the strong influence on the acceptance of the perturbation of the ion trajectories by the magnetic fields. In this example also, the "knee," or region of greatest curvature, in the plot is much more pronounced than is the case with the field on.

A test of the acceptance code was performed by calculating the acceptance with the magnetic fields off and negligible multiple scattering. The calculated acceptance came out to be .995, very near the nominal 1.00.

The Monte Carlo acceptance calculations were done with a sufficient number of events to give statistical uncertainties no worse than 6.5 percent. The uncertainty in the acceptance for ions with very good acceptance approached

Fig. 3.13.--Telescope Acceptance for He Ions. Open circles and triangles indicate acceptance for beam spots with one-half and one-and-one-half time the nominal diameter respectively. Also shown is the acceptance with no perturbing magnetic fields.

Fig. 3.14.--Telescope Acceptance for Li Ions

Fig. 3.15.--Telescope Acceptance for Be Ions

Fig. 3.16.--Telescope Acceptance for B Ions

Fig. 3.17.--Telescope Acceptance for C Ions

Fig. 3.18.--Telescope Acceptance for N Ions

Fig. 3.19.--Telescope Acceptance for O Ions

2.5 percent. These uncertainties are related to the geometry of the solid angle determination.

The solid angle of the telescope was determined by photographing the image of the angle of the telescope on a particle detector in the target. This gave an effective solid angle which was used in the cross section calculation. The effective solid angle differed from the geometrical solid angle shown in Chapter 2 because of a restriction of the beam spot being incident on the entrance of the telescope that the entrance aperture obscured part of the full aperture of the telescope. The resulting reduced solid angle, 6.49×10^{-6} steradians, was used in the cross section calculation, but those results corrected only for the limitation in the yield resulting from perturbation of particle trajectories for the detector. The cross section calculation still required that the telescope solid angle used be corrected for the reduced solid angle available to the particles emerging from the target far out on the wings of the beam spot. The effective solid angle was determined to be 6.49×10^{-6} steradians, which was 14.8 percent smaller than the geometrical solid angle.

Detector Efficiencies

This section deals with the efficiencies of the time-pick-off detectors. An understanding of these efficiencies was necessary for correcting the particle energy spectra and for understanding some of the physics of these detectors. Two methods were used to measure the efficiencies, one being a direct measurement, and the other employed a theoretical model. This model, which parameterizes the secondary electron emission and the signal amplitude, was corroborated by the direct measurements. The efficiencies of all the other telescope detectors were taken to be one-hundred percent for the particles of interest.

The total signal obtained is dependent on the dependence of the secondary electron emission on the ionization rate, which in turn, depends on the ion charge and velocity. Since both the ionization energy loss rate and secondary electron emission are the consequence of collisions of the ion with atomic electrons in the stopping material, it was assumed that they could be expressed as the same function of the ion charge and velocity. Hence, one can write,

$$n = \alpha' dE/dx \quad (3.25)$$

where n is the average number of secondary electrons knocked out of the foil, and dE/dx is the energy loss rate. In the determination of α' , one takes the AL signal to be proportional to the dE/dx in the carbon foil, so that, in fact, one wants to determine alphas such that,

$$n = \alpha' E. \quad (3.26)$$

It was further assumed that the probability for a given number of secondary electrons, n , to be emitted from a carbon foil followed a Poisson distribution

$$P(n) = e^{-\bar{n}} \frac{\bar{n}^n}{n!}. \quad (3.27)$$

Finally, the average amplitude of the time-pick-off signals, $\bar{A}$, was taken to be a linear function of the average number of secondary electrons striking the channeltron electron multiplier

$$\bar{A} = \beta \bar{n}_s. \quad (3.28)$$

Effectively, β was a measure of the gain of the secondary electron transport and amplification system.

With the determination of α , the corresponding efficiency was just a consequence of the assumed Poisson statistics. The probability that at least one secondary electron will be emitted is

$$\bar{E}_1 = 1 - P(0) .$$

Which, upon substitution of the expression for the probability of no electrons being emitted in the Poisson distribution, yields

$$\bar{E}_1 = 1 - e^{-\bar{n}} = 1 - e^{-\alpha \Delta E} . \quad (3.29)$$

The efficiency is expressed here as a function of ΔE .

From the above assumptions one can derive a functional form for the signal amplitude as a function of ΔE . The value of $\bar{n}_s$ can be expressed in terms of the Poisson distribution as

$$\bar{n}_s = \frac{\sum_{n=1}^{\infty} P(n)n}{\sum_{n=1}^{\infty} P(n)} = \frac{\sum_{n=0}^{\infty} P(n)n}{\sum_{n=0}^{\infty} P(n) - e^{-\bar{n}}} .$$

This simplifies to

$$\bar{n}_s = \frac{\bar{n}}{1 - e^{-\bar{n}}} \quad (3.30)$$

which, upon substitution of Eq. (3.26) for $\bar{n}$, gives the following equation for the average signal amplitude,

$$\bar{A} = \beta \left(\frac{\alpha \Delta E}{1 - e^{-\alpha \Delta E}} \right) . \quad (3.31)$$

The parameters α and β were determined in the following way. For small values of ΔE , Eq. (3.31) approaches $\beta(1 + 1/2 \alpha \Delta E)$. From this it is seen that the $\bar{A}$ -intercept gives β . As ΔE becomes large Eq. (3.31) asymptotically approaches the line $\bar{A} = \alpha \beta \Delta E$. The slope of the asymptote in combination with the $\bar{A}$ -intercept determines α and β .

Figures 3.20 and 3.21 show plots of $\bar{A}$ versus ΔE data for the T_1 and T_2 detectors with cuts having been made on charge two and charge three

Fig. 3.20.--Plots of $\bar{A}_1$ and $\bar{A}_2$ Versus ΔE Data for Efficiency Determinations of Charge Two Fragments Along with Best Fit given by Eq. (3.30).

Fig. 3.21.--Plots of $\bar{A}_1$ and $\bar{A}_2$ Versus ΔE Data for Efficiency Determination of Charge Three Fragments Along with Best Fit Given by Eq. (3.30). Closed circles are charge two data points.

fragments respectively. Also shown are estimates of the asymptotes and plots of the theoretical signal amplitudes derived using Eq. (3.31) and α 's and β 's giving the best fit to the experimental data points. Extrapolation from the charge two data to the $\bar{A}$ -intercepts gave a β of 8.00 for the T_1 detector and 8.25 for the T_2 detector. This, combined with the slopes of the asymptotes, gave α 's of 6.94 and 6.52 for T_1 and T_2 respectively. Figure 3.22 contains plots of the detector efficiencies calculated using Eq. (3.29) and the above α 's for each detector.

Determining β for ions with charges greater than two was difficult since these fragments had no yield giving very small ΔE signals. Hence, the extrapolation to the $\bar{A}$ -intercept was ambiguous. To assist in the estimation of β for $Z=3$ data it was necessary to plot some $Z=2$ data points for values of ΔE less than .25 MeV. These charge two data points appeared to fit continuously with the other data. For charge three fragments the α 's were determined to be 6.10 and 6.65 for T_1 and T_2 respectively. These values are not greatly different from the charge two values. Efficiencies calculated for the charge three fragments differed from charge two values by no more than 5 percent at the same ΔE amplitudes. This indicated that the efficiencies were essentially independent of charge. Consequently, the same α 's were used for determining the efficiencies of each species.

In addition to the efficiencies calculated using Eq. (3.29) and the aforementioned α 's, Fig. 3.22 shows direct efficiency measurement data points and a fitted curve. These data were taken on the T_2 detector in the following way. Data were taken on the aluminum target in the $T_1 \cdot E_1$ logic mode. Cutting on an interval of ΔE signal amplitudes, histograms were made of the T_2 signal amplitudes. The ratio, R , of events with T_2 equal to zero to events with T_2 non-zero was determined. The number of events with T_2 absent can be written as

Fig. 3.22.--Efficiency as a Function of ΔE for 90° Data

$$T_1 \cdot E_1 = (1 - \xi_2) \xi_1 N \quad (3.32)$$

where ξ_1 and ξ_2 are the T_1 and T_2 efficiencies and N is the total number of incident particles on the detectors. Similarly, the number of events with T_2 non-zero can be written as

$$T_1 \cdot T_2 \cdot E_1 = \xi_2 \xi_1 N \quad (3.33)$$

Dividing Eq. (3.32) by (3.33) the left-hand-side gives the ratio R , and one can solve for the T_2 efficiency,

$$\xi_2 = 1/1+R. \quad (3.34)$$

The statistics were such that efficiency determinations as a function of the particle charge were not possible by direct measurement. However, the second technique described at the beginning of this section indicated that the efficiencies were insensitive to charge. Agreement between the two efficiency measurements was good. Similar comparisons made with data taken prior to the production data runs showed excellent agreement. A bench test of the time-pick-off detectors with a monoenergetic alpha source also agreed with these measurements. As a consequence of the excellent agreement between the two techniques, Eq. (3.30) was used to determine the efficiency corrections applied to the particle yields. Figure 3.23 shows the T_2 efficiencies calculated for each of the ions of interest as a function of E/M . This was done by determining the efficiency for a given ion at a specific value of ΔE and mapping this to a corresponding value of E/M .

The efficiencies were found to be poorer for the data taken at 30° . The direct measurement and the technique modeling the time-pick-off detectors were in agreement, and each indicated the efficiencies were poorer at 30° than during previous data runs. The results of the efficiency measurements at 30°

Fig. 3.23.--Time-Pick-Off Detector Efficiency as a Function of E/M for Each of the Charge States for 90° Data

are shown in Fig. 3.24, where the efficiency of T_2 is plotted as a function of E/M for each element. The ions most affected by this reduced efficiency are the $Z=2$ and, to a smaller extent, the $Z=3$ fragments. The large corrections to the spectra for $Z=2$ fragments, especially at large E/M , indicated that the telescope was most effective in detecting ions which were more heavily ionizing than $Z=2$ fragments of a few MeV/amu. The effects of the efficiency corrections will be discussed further in the final chapter.

Target Effects

Corrections had to be made to the energy spectra to account for energy losses of the product ions in the target. The actual ion energy resulting from the spallation was different from the measured energy by the amount of energy lost by the ion in traversing the target. These energy losses were only a small fraction of the total ion energy in most instances and amounted to a small shift to higher energy in the low energy part of the spectra.

Since the energy losses were small compared with the total ion energy, a few simplifying assumptions were made to facilitate calculation of the target correction. The ion products were taken to originate in the middle of the target thickness, which was the average position for fragment production since the beam intensity was not appreciably attenuated by the target. The stopping powers varied by no more than 10 percent between the measured energies and the actual energies, so stopping powers were taken to be those of the measured fragment energies. The spectral data were plotted such that data points were adjusted along the E/M -axis to reflect target corrections if those corrections amounted to more than one-quarter of a bin width. The uncertainty in the correction due to the target was taken to be no more than 10 percent.

Fig. 3.24.--Time-Pick-Off Detector Efficiency as a Function of E/M for Each of the Charge States for 30° Data

Differential Production Cross-Section Calculations

The final cross-section calculation required determination of the number of incident protons on the target, in addition to the yield of product fragments corrected for background, efficiencies, and acceptance. The attempt to monitor the current by means of scaling the toroid and clock failed due to a malfunction of unknown origin. Consequently, the number of incident protons, I , was determined from the average current reported from current monitor number 2 and the length of the data run. For each target and angle a sufficient percentage of the data were found for which the beam current was constant and uninterrupted that these data could be used to do an absolute normalization. Those runs where the beam current changed or where the current was intermittent were normalized against the stable current runs by scaling the yields in the alpha spectra between 2.0 and 3.0 MeV/amu. The uncertainties in the currents and lengths of the data runs resulted in an assigned 15 percent uncertainty in the total number of protons for each target and angle.

The position and profile of the beam spot on the target was monitored by a wire scanner approximately one meter downstream of the target. As noted earlier, the beam profile would often vary at this monitoring position, while the beam tune remained unchanged and wire scan profiles further upstream showed minimal, if any, variation at their positions. The very low operating beam current was at the limit of the wire scanners performance level. Consequently, reliance was put upon upstream monitors and the stability of the beam tune to assure that the drifts in the spot profile were not excessive.

The telescope would accept particles with finite probability from the target so long as they were within the circumference of the penumbra of the telescope. The penumbra was defined by the geometry of the entrance aperture of the telescope and the sensitive area of the E_1 detector. The reduced solid angle of particles originating outside the umbra, but within the penumbra, was accounted for and calculated by acceptance code. The penumbra of the telescope

on the target position was a circle 2.04 cm in diameter. The beam spot on the target was very well focussed in the vertical sense and the profiles were very nearly gaussian. In the horizontal sense the beam was often irregular in shape and occasionally, at higher currents, a gaussian shape was evident. However, the spot width varied over a much greater range in the horizontal. Assuming that the tune was steady enough not to cause significant deterioration of the profile at lower currents, where the wire scanners failed to give adequate read-outs, the data indicated that the penumbra encompassed more than two standard deviations of the spot intensity. The telescope alignment was done such that the axis of the telescope was within 1.0 mm of the target center. The beam profiles indicated the center of the beam spot rarely exceeded a displacement of a few millimeters from the center of the target. From the preceding considerations it was assumed that the telescope accepted particles from 90 ± 10 percent of the beam spot on target.

The yield of a given species in some range of energy was calculated from the following relation

$$Y = \left(\frac{Y'}{\ell'} - \frac{B}{\ell} \right) / \epsilon A \quad (3.35)$$

where Y' was the raw yield from the data tapes, B was the background, ℓ' was the live-time of the data acquisition system during the production run, ℓ was the live-time during the background run, ϵ was the efficiency correction, and A was the acceptance correction. Background, or target-out, runs were made with a blank target frame on the target ladder. In the case of the data taken at 90° the positioning of the target ladder with respect to the axis of the telescope caused a small fraction of the penumbra of the telescope to encompass some of the Kapton target holder. Subtraction of background events consequently was important. The background runs proved very time-consuming and, as a result, the statistics for the background runs were not great and

led to a significant source of uncertainty in the yields. The efficiencies, acceptance and corrections due to the target have all been discussed in previous sections.

Calculations of the final differential cross sections were made from the following

$$\frac{d^2\sigma}{dEd\Omega} = \frac{Y/\Omega}{I(n\Delta x)} \quad (3.36)$$

where Y was the yield of a given species at the energy of interest, Ω was the effective solid angle of the telescope, I was the number of incident protons, n was the number of target nuclei per unit volume and Δx was the target thickness. Estimation of the uncertainties for those factors which bear upon the calculation of the yields and integrated proton flux have been discussed in the sections dealing with those contributions. The solid angle of the telescope was taken to be known to 5 percent, and the uncertainties assigned the target thicknesses were 10 percent. The yields were compiled in E/M bin widths which gave no worse than 20 percent statistical uncertainty over the range of interest.

CHAPTER 4

THEORETICAL MODEL AND COMPUTER CODES

This chapter deals with the theoretical aspects of proton spallation. A description will be given of the reaction mechanism and the computer code used to model these reactions. The results of the theoretical calculations will be given in the following chapter where comparison will be made with the experimental differential cross-sections.

Spallation generally refers to high energy nuclear reactions in which the target nucleus is spalled into several fragments by an incident particle. There can be several competing processes, the relative importance of each depending upon the mass of the target nucleus and the species and energy of the incident particle. The predominate processes are intra-nuclear cascade and nuclear evaporation, which involve the emission of nucleons and particles with masses no greater than the alpha particle. These mechanisms form the basis for the computer calculations presented in this dissertation. At very high energies and for more massive targets competition from other mechanisms such as fragmentation, fission, and evaporation of particles heavier than alphas is expected to become increasingly important.

Two Stage Reaction Model

The framework for most theoretical studies of high energy nuclear reactions is a two step model originally proposed by Serber.³² The reaction is thought of as proceeding from an initial "fast" or "cascade" stage to a "slow" or "evaporation" stage. The conditions for the cascade stage will be

outlined below. These conditions preclude a compound nucleus model which would apply at lower energies. The second stage of evaporation treats the residual excited nucleus left from the cascade stage. This analysis is independent of the reaction mechanism which led to the excited product.

For the high incident energy of this experiment the mean free path of the incident proton, λ , is much less than the nuclear radius, R . Many scatterings occur inside the nucleus so that interference terms between the scattered waves tend to cancel out. Furthermore, the mean free path is much larger than the de Broglie wavelength, $\hbar$, and scattered waves will approximately reach their asymptotic values before the succeeding scattering. This indicates that a classical treatment of the scattering suffices. Finally, if the mean free path is significantly greater than the interparticle distance, d , the scatterings from the nucleons within the nucleus can be assumed to be independent of each other. What transpires in the initial stage of a reaction depends upon the particular trajectory of the incident particle within the nucleus and, hence, upon the number of independent collisions experienced. Each collision is taken to be that of free particles. The struck particles will have lower energies and shorter mean free paths. These particles are likely to escape the nucleus without further collisions only if they are struck near the edge of the nucleus. Subsequent collisions constitute the cascade, with the struck nucleons either leaving the nucleus or losing sufficient energy in ensuing collisions to be trapped. Once the cascade is completed, the fraction of the initial collision energy remaining constitutes an excitation energy of the residual nucleus.

During the evaporation stage the excitation energy of the residual nucleus is dissipated by the emission of particles with several million electron volts of kinetic energy. Treatment of this last stage is based on the statistical model of the nucleus proposed by Weisskopf.³³ Particles within

the nucleus which are considered as candidates for evaporation are thought of as having energy distributions within the excited nucleus characteristic of the temperature of the nuclear matter. The probability for emission of a certain species of particle will depend upon the probability of such a particle being energetic enough to escape the potential-well of the nucleus. Consequently, the spectra of these charged emission particles are characterized by the Coulomb barrier and the temperature, or excitation, of the nuclear matter of the residual nuclei. Both of these characteristics will be strongly influenced by the size and excitation energy of the residual nucleus. Highly excited nuclei will undergo successive evaporations and the measured spectra will be superpositions of different emission spectra from intermediate nuclei at each step in the evaporation process. Following each evaporation the nuclear temperature is decreased and the Coulomb barrier is reduced for those charged particles emitted in further evaporations. These two effects led to a broadening of the emission spectrum of particles from highly excited nuclei.

The two stage picture outline above predicts four types of reaction products: (1) prompt cascade nucleons emitted with a broad spectrum of energies ranging up to the energy of the incident particle. Alpha particles or other aggregates of nucleons in transient clusters in the nucleus may also be ejected. For energies sufficiently large for pion production, these too may be emitted; (2) evaporation yields nucleons and nucleon aggregates emitted isotropically in the residual nucleus center-of-mass; (3) the residual nuclei of the evaporation, and; (4) fission products.

Theoretical Computer Codes

Some more details of the two stage model sketched above will be given in the following discussion of the theoretical computer codes. The picture

presented readily lends itself to Monte Carlo type calculations. Such calculations were first attempted by Goldberger,³⁴ and the basic assumptions of his work are the same as those used in the current computer code which performed calculations for the cascade stage. This code, commonly known as VEGAS, has undergone various changes since calculations from the original version were first published by Metropolis et al.^{1,2} Some of the fundamental assumptions of this code in its present form at the Los Alamos Scientific Laboratory will now be discussed.

The target nucleus is taken to be a mixture of two non-interacting Fermi gases of neutrons and protons bound in a nuclear potential. The maximum Fermi energies of the protons and neutrons are given by

$$E_F = (\hbar^2/2m) (3\pi^2 N/V)^{2/3} , \quad (4.1)$$

where N is the number of neutrons or protons, V is the nuclear volume, and m is the mass of the nucleon. The cross sections for collisions between the incident proton and nucleons in the nucleus and subsequent collisions in the cascade are taken to be those measured for free nucleon-nucleon scattering. The justification for this has been discussed in the previous section. One nuclear effect taken into account is the Pauli exclusion principle. The Pauli principle requires that the momenta of the incident and struck nucleon after collision be outside the occupied sphere in momentum space. The radius of the sphere is given by

$$p = \hbar (3\pi^2 N/V)^{1/3} . \quad (4.2)$$

This has the effect of forbidding a sizeable fraction of collisions and increasing the mean free path of the incident particle and, later, the struck nucleons. Particles are treated as cascade particles so long as their

energies inside the nucleus are above a certain cut-off. This cut-off depends upon the particle, but for a proton it is taken to be approximately equal to the kinetic energy a proton would need to escape the Coulomb barrier at the nuclear surface.

Several other capabilities of the VEGAS code reflect features incorporated since the original calculation by Metropolis et al.^{1,2} Distributions of nuclear density and potential energy can be accounted for. Along with this, refractions and reflections of particles at boundaries between regions of the distribution and at the nuclear surface are treated. The VEGAS calculation is also able to account for pion production, pion scattering and charge exchange, and pion absorption. These calculations utilize the isobar model proposed by Sternheimer and Lindenbaum.^{35,36,37} The isobar model will not be discussed in this dissertation.

The calculation outlined above allows emission of protons, neutrons, π^+ , π^- , and π^0 particles during the cascade stage of the reaction. No account is made for the interaction of the incident particle with aggregates of nucleons. Consequently, the possibility of cascade emissions of deuterons, tritons, alpha particles, or more massive particles is disregarded. The outcome from the VEGAS calculation includes the atomic numbers, atomic masses and excitation energies of each of the residual nuclei generated. Additionally, for each of the cascade particles emitted, up to a limit of 30 particles, the following information was recorded: the species of the particle, the kinetic energy, the particle mass, and the direction cosines of the particle momentum vector. It is from this information that calculations of theoretical differential cross sections were made using a second computer code that did Monte Carlo evaporations in the center-of-mass of the excited residual nuclei.

The fate of the excited nucleus remaining following emission of the cascade particles was treated by a second computer code. This is, again, a

Monte Carlo calculation and the results of this code were first reported by Dostrovsky, Rabinowitz, and Bivens in 1958.³ The only effective means of de-excitation for nuclei with large excitations such as those of interest here is particle emission. The treatment is based on the statistical model and it starts with the formula of Weisskopf,³³

$$P_j(\epsilon)d\epsilon = \gamma_j \sigma \epsilon [\rho(f)/\rho(i)]d\epsilon, \quad (4.3)$$

where $P_j(\epsilon)d\epsilon$ is the probability per unit time of emission of a particle j with kinetic energy between ϵ and $\epsilon+d\epsilon$, σ is the total cross section for capture of particles j by the final nucleus, and $\rho(f)$ and $\rho(i)$ are the level densities of the final and initial nuclei. Also, $\gamma_j = gm/\pi^2 h^3$, where g is the number of spin states and m is the mass of particle j .

Using this fundamental equation and the assumption of the nucleus being represented by a degenerate Fermi gas, the calculation of the relative probabilities of emission of the various particles is made possible. These probabilities are recalculated after the emission of each particle. The calculation is made using the statistical model level density formula, which leaves the level density parameter and particle binding energies as required input to the code. The level density parameter is left as a free input parameter. The required binding energies are stored in mass excess tables within the code. Also, of fundamental importance is the determination of the Coulomb barrier and the handling of the tunneling effect.

Computer Code Modifications

The particles considered as candidates for evaporation were neutrons, protons, deuterons, tritons, ³He and alpha particles. In order to obtain the required differential production cross-sections for the various particles detected experimentally, it was necessary to make several additions to the

evaporation code outlined above. The existing code only did evaporations of excited nuclei in their own center-of-mass frame of reference. Also, only total cross-sections for the residual nuclei were tabulated, no accounting being made of the angular distributions. Finally, no accounting was kept of the emission particles.

In order to determine the angular distributions of the recoil nuclei in the laboratory frame the momentum of the residual nucleus from the cascade was determined. This was done by summing the momenta of the cascade emission particles and subtracting these from the momentum of the incident proton. These calculations were all done relativistically. After the excited residual nucleus was allowed to evaporate isotropically in its center-of-mass, the momenta of the new residual and the evaporation product were calculated and transformed to laboratory coordinates. If the evaporated particle was either a ^3He or an alpha particle a test was made on the angle at which the particle emerged. If the event satisfied the solid angle requirements it was tabulated according to its energy. The new recoil nucleus was followed through successive evaporations until the excitation energy was so low as to preclude further particle emissions. The momentum of this final product was tested against the prescribed solid angle, and energy distributions were determined for these recoil nuclei.

The final differential cross-sections were calculated in the following way,

$$\frac{d^2\sigma}{dE d\Omega} = \frac{Y(Z,A,\Delta E)G}{10 C(\Delta E)(\Delta\Omega)} \quad (4.4)$$

Here, $Y(Z,A,\Delta E)$ is the total yield of a given particle species over a prescribed range of energy. The factor G is the geometrical cross-section, ΔE is the width of the energy bin, $\Delta\Omega$ is the solid angle, and C is the number of initial cascades generated by the code. The factor of ten arising in the

denominator accounts for the fact that ten independent evaporations were initiated for each of the excited products of the cascade code. This was done to improve the statistics in the evaporation stage. The geometrical cross-section was calculated from

$$G = \pi R^2 (1 - V_c/\epsilon_{inc}) , \quad (4.5)$$

where R is the nuclear radius, $R = 1.07A^{1/3} + 2.5 F$, V_c is the Coulomb barrier, and ϵ_{inc} is the kinetic energy of the incident particle.

The solid angle was taken to be an annular cone symmetric about the Z-axis defined by the incident particle. Since computer time was costly, and the cross-sections were not thought to have strong angular dependence, fairly large solid angles were chosen so as to facilitate achieving the greatest statistics practicable. For comparison with the experimental data at 30 and 90 degrees, the Monte Carlo code took solid angles where θ ranged from 15 to 45 degrees and 75 to 105 degrees, respectively. The energy distributions were accumulated in bins of E/m 0.25 MeV/amu wide.

The results of the theoretical calculations are presented in the following chapter where they are compared with the experimental measurements. Where the theoretical calculations proved to have inadequate statistics, no results are presented. This is the case for many of the lighter residual products from the nickel target. These products are improbable because of the high excitation energy and large number of evaporations required to leave such a recoil nucleus. In order to achieve acceptable statistics 25,000 cascades were done on carbon and aluminum and 30,000 cascades were done on nickel.

It should be noted that this theoretical treatment has not attempted to account for competing processes such as fission, emission of nuclear

aggregates as cascade products, the evaporation of particles more massive than alpha particles, or fragmentation.

CHAPTER 5

RESULTS AND CONCLUSIONS

Survey of Results

This chapter presents the results of the experimentally measured differential cross sections as well as the theoretical predictions of the computer codes discussed in the last chapter. These differential cross sections have been integrated over the energies measured so that a value representative of the partial production cross section for each of the species could be obtained. This facilitates comparison of relative yields and comparison with values in the literature. The results are discussed and an interpretation is presented which attempts to shed some light on the successes and inadequacies of the theoretical model. Preceding the indepth discussion and interpretation of the results a section is presented discussing problems which were encountered during the course of the experiment and analysis which bear upon the results. This is followed by a section in which the experimental apparatus and technique are examined and improvements are suggested. The final section presents the interpretation of the results, along with comparisons with other measurements and the theoretical code, and the physics conclusions that can be drawn from the experiment.

The resolutions achieved were discussed at length in Chapter 3. These resolutions allowed the clean separation of each of the isotopes of the elements helium through carbon. The isotopes of nitrogen and oxygen were less resolved, with histograms of these isotopes showing considerable overlap of the different masses. Consequently, the individual production cross sections

were not determined for each isotope, but for the entire element. The following species gave sufficient yield to warrant calculation of their individual production cross sections: ^3He , ^4He , ^6Li , ^7Li , ^7Be , ^9Be , ^{10}Be , ^{10}B , ^{11}B , ^{11}C , ^{12}C , and ^{13}C . Additionally, small yields of ^6He and ^8Li were found, and, for aluminum, considerable production of fluorine was observed. The fluorine data were not analyzed due to the difficulty of extracting the intrinsic charge resolution for these very low velocity fragments.

The differential production cross sections for the products from the carbon target are given in Figs. 5.1 through 5.10. The data at both 30° and 90° are given in each figure, as well as the predictions of the Monte Carlo code at these angles and, when available, some values from the literature. The cross sections for the aluminum target are given in Figs. 5.11 through 5.24, and the nickel data are presented in Figs. 5.25 through 5.38. Representative error bars are given on approximately every third data point. These error bars reflect statistical uncertainties, and uncertainties in the acceptance and efficiency corrections. Absolute uncertainties bearing upon the normalization of the cross sections have been given in Chapter 3 and some will be discussed further below. These latter uncertainties include those for the integrated proton flux, the target thickness, and the solid angle. No error bars are given for the Monte Carlo computer code calculations as their value is overridden by the confusion introduced by the increased density of information in the figure. Limits on computer time dictated that some of the computer predictions were to have poor statistics, and this can be seen in the large scatter of the data points in some spectra. For nickel, in fact, there was insufficient yield (or no yield) of some species to justify plotting the calculations on these figures. The ^4He spectra from each of the targets show fiducial spikes which are a consequence of the alpha calibration source.

Fig. 5.1.--Differential Production Cross Section for ${}^3\text{He}$ from Carbon

Fig. 5.2.--Differential Production Cross Section for ⁴He from Carbon

Fig. 5.3.--Differential Production Cross Section for ${}^6\text{Li}$ from Carbon

Fig. 5.4.--Differential Production Cross Section for ^{7}Li from Carbon

Fig. 5.5.--Differential Production Cross Section for
 ${}^7\text{Be}$ from Carbon

Fig. 5.6.--Differential Production Cross Section for ${}^9\text{Be}$ from Carbon

^{10}Be FROM C
 Fig. 5.7.--Differential Production Cross Section for ^{10}Be from Carbon

Fig. 5.8.--Differential Production Cross Section for ^{10}B from Carbon

Fig. 5.9.--Differential Production Cross Section for ¹¹B from Carbon

Fig. 5.10.--Differential Production Cross Section for ^{11}C from Carbon

Fig. 5.11.--Differential Production Cross Section for ${}^3\text{He}$ from Aluminum

Fig. 5.12.--Differential Production Cross Section for ${}^4\text{He}$ from Aluminum

Fig. 5.13.--Differential Production Cross Section for ${}^6\text{Li}$ from Aluminum

Fig. 5.14.--Differential Production Cross Section for ${}^7\text{Li}$ from Aluminum

Fig. 5.15.--Differential Production Cross Section for ${}^7\text{Be}$ from Aluminum

Fig. 5.16.--Differential Production Cross Section for ^{9}Be from Aluminum

Fig. 5.17.--Differential Production Cross Section for ^{10}Be from Aluminum

Fig. 5.18.--Differential Production Cross Section for ^{10}B from Aluminum

Fig. 5.19.--Differential Production Cross Section for ¹¹B from Aluminum

Fig. 5.20.--Differential Production Cross Section for ^{11}C from Aluminum

Fig. 5.21. -- Differential Production Cross Section for ^{12}C from Aluminum

Fig. 5.22.--Differential Production Cross Section for ^{13}C from Aluminum

Fig. 5.23.--Differential Production Cross Section for N from Aluminum

Fig. 5.24.--Differential Production Cross Section for O from Aluminum

Fig. 5.25.--Differential Production Cross Section for ^3He from Nickel

Fig. 5.26.--Differential Production Cross Section for ^4He from Nickel

Fig. 5.27.--Differential Production Cross Section for ${}^6\text{Li}$ from Nickel

Fig. 5.28.--Differential Production Cross Section for ${}^7\text{Li}$ from Nickel

Fig. 5.29.--Differential Production Cross Section for ^{7}Be from Nickel

Fig. 5.30.--Differential Production Cross Section for ${}^9\text{Be}$ from Nickel

Fig. 5.31.--Differential Production Cross Section for ^{10}Be from Nickel

Fig. 5.32.--Differential Production Cross Section for ^{10}B from Nickel

Fig. 5.33.--Differential Production Cross Section for ^{11}B from Nickel

Fig. 5.34.--Differential Production Cross Section for ^{11}C from Nickel

Fig. 5.35.--Differential Production Cross Section for ^{12}C from Nickel

Fig. 5.36.--Differential Production Cross Section for ^{13}C from Nickel

Fig. 5.37.--Differential Production Cross Section for N from Nickel

Fig. 5.38.--Differential Production Cross Section for O from Nickel

Figure 5.39 displays the production cross sections for all of the products from the carbon target. These are curves fitted to the data at 90° . Similarly, Fig. 5.40 summarizes the cross sections for the products from the aluminum data, and Fig. 5.41 summarizes the nickel data. Generally, the spectra display the forms expected. That is, as suggested in Chapter 1, the helium spectra, and to a small degree the lithium spectra, display the features of evaporation-like spectra, and the larger mass fragments show spectra characteristic of recoil nuclei. Unfortunately, the salient features of the helium spectra are only marginally valuable as a result of large corrections applied to the spectra of these, the most lightly ionizing of the fragments detected. The problems associated with the helium spectra are discussed in the following section.

Experimental and Analytic Problems Affecting the Results

Several problems were encountered during the final stages of the analysis. This section will discuss those problems, the manner in which the spectra were influenced, and the uncertainties introduced. These problems fall into three categories: absolute normalization due to uncertainties in the integrated proton flux, background subtraction, and efficiency corrections.

The uncertainties in the integrated proton flux bear upon both the absolute normalization of the spectra as well as the background subtraction problem. The uncertainty in the integrated proton flux reflects uncertainties in the beam current, the running time for each data run, the amount of the beam incident on the target and the stability of that beam spot distribution. Upon discovering that our scaling of the toroid current monitor was unreliable, we found it was necessary to use currents and running times recorded in the experiment log books. As described in Chapter 3, sufficient data were found for each target and angle to do an absolute normalization, however, an

Fig. 5.39.--Differential Production Cross Sections from Carbon Target at 90°

Fig. 5.40.--Differential Production Cross Sections from Aluminum Target at 90°

Fig. 5.41.--Differential Production Cross Sections from Nickel Target at 90°

assigned uncertainty of 15 to 20 percent for these time-integrated currents is not unreasonable.

The problem associated with the horizontal beam spot profile have been discussed in earlier chapters. The constancy of the beam tune was checked by monitoring wire scanners both upstream and downstream of the experiment. Also, the focusing and steering of the beam was checked by reviewing the quadrupole and bending magnet currents of the beam line. Though these checks indicated a stable beam tune, there are several other indications of instability. Though the fluxes at the nearest wire scanner were too low for accurate monitoring of the beam profile in the horizontal sense, it was possible to see some qualitative features that would indicate the beam was broader on some occasions than others. The singles rates in the time-pick-off detectors changed frequently with no apparent change in either beam current or tune. This could have reflected mere fluctuations on the wings of the beam profile affecting background radiation from the beam, or it could reflect more serious loss of incident beam on the target. Similarly, the event rates showed substantial fluctuations when normalized to a standard current. Most revealing is the fluctuation in the event rate during background runs where the blank on the target ladder was positioned in the beam. This instability in the background rate, along with the rather large uncertainties in the time-integrated proton flux made the background subtraction difficult. This was especially true for species which had low event rates from the target, and, also, high rates from the Kapton target holder. This was the case most often with the larger mass fragments from the nickel target. The problem was much less severe for the 30° data than the 90° data since the background rates were much lower at the forward angle as a result of a more favorable alignment of the beam, target ladder and telescope. The specific

spectra most likely to be distorted by these uncertain background subtractions will be pointed out in the course of this chapter.

The background subtraction was further complicated by alphas from the calibration source being degraded through the Kapton and polluting the alpha spectra below about 0.75 MeV/amu. The fraction of alphas appearing in the spectra which was degraded in this manner was not constant, and so, the ^4He spectra are considered unreliable below 0.75 MeV/amu.

Finally, as noted in Chapter 3, the time-pick-off detector efficiencies were lower during the 30° data runs. The reason these final data showed lower efficiencies than previous data was not completely understood. The effect of the lower efficiencies was to cause the alpha cross sections at 30° to be lower than expected. That is, they were lower than the 90° data. Though the lithium spectra might be expected to be influenced fairly strongly by the lowered efficiency, no element other than helium gave results in which the 30° cross sections were lower than the 90° cross sections. This disparity existed even after new efficiency corrections were determined for the 30° data, and so, it is concluded that the efficiencies at 30° were particularly bad for the most lightly ionizing products, ^3He and ^4He , and that the spectra of these fragments are unreliable.

In fact, the efficiency and acceptance corrections, when taken together for the helium ions, proved to dominate over the data in such a way as to cause a probable masking of "true shape" of the spectra. The corrections cause the helium spectra from each of the targets to peak at nearly the same energy, around 2.25 MeV/amu. This is not reasonable if the peak is characteristic of the nuclear coulomb barrier. Also, the efficiencies of the most lightly ionizing of these alpha particles were very difficult to determine. For helium fragments on the order of 3 MeV/amu the energy deposition in the ionization chamber was approaching 0.1 MeV, where a threshold in the

software discriminated against such lightly ionizing fragments. The alpha efficiencies beyond 3 MeV/amu were extrapolated from the data at lower velocity, however, the yields of these alphas are sufficiently suspect as a consequence of the software threshold that the spectra are considered unreliable in this region. This is true, even in the cleanest range of from 0.75 to 3.0 MeV/amu, because of the sensitivity of the data to the large corrections. It will be shown that the measured helium spectra are in substantial disagreement with other experimental measurements and the theoretical code. The bulk of the succeeding discussion will focus upon the more heavily ionizing fragments which are the main thrust of this experiment since more conventional techniques are available for studying lightly ionizing particles.

Conclusions Regarding Apparatus and Experimental Performance

The detectors developed in this experiment proved to be quite successful in achieving the objective of measuring the differential cross sections of very short ranged spallation products from high energy reactions. The quality of most of the data for fragments more massive than helium is good. The deficiencies in the experiment were primarily the result of conditions independent of the individual detector performances. That is, the problems stemmed from beam spot instabilities which were a consequence of the poor location in the beam line. This made achievement and monitoring of a good beam tune difficult. Retaining the monitor telescope as a relative monitor of beam on target could have aided in overcoming some of this problem with the stability of the beam spot profile. Also, a malfunction of the scaling of the beam current toroid monitor generated large uncertainties. It might also have been valuable to have had more background runs taken intermittently throughout the production runs. Better statistics for backgrounds

alone would have been helpful along with a better measure of the constancy of the background rates throughout the data taking.

Though the detectors performed well, two design considerations would improve the overall performance of any future such telescope. These changes would point to improving the acceptance of the telescope and the reliability of the acceptance corrections. Multiple scattering was a significant factor influencing acceptance, which was substantially lowered by the perturbation of the ion trajectories by the magnetic fields of the time-pick-off detectors. The electron transport of these detectors could be designed so as to allow weaker magnetic fields resulting in smaller perturbations of the passing heavy ions. Also, compensating magnetic fields could be introduced before and after each detector, or, more simply, the two time-pick-off detectors could be rotated with respect to each other by 180 degrees about the axis of the telescope. This last modification would, at least, ensure that the perturbations introduced by each detector would not compound one another.

Finally, it now seems apparent that the acceptance was very sensitive to the alignment of the telescope apertures. Great care had to be given the alignment of the small one centimeter apertures of the time-pick-off detectors, the ionization chamber windows, and the silicon detectors. Larger apertures would have aided in assuring the reliability of the acceptance corrections since small misalignments would have had less severe effects. These larger apertures would have been difficult to construct since the windows and foils required by this experiment were very thin and delicate.

The following section discusses in greater detail the successes of the experiment and the implications these results might have upon the theoretical reaction model.

Discussion of Results and Conclusions

This section discusses the general features of the differential cross sections and compares these results with measurements reported in the literature and the computer code predictions. Values representative of total cross sections were calculated from the experiment and code to assist in comparisons of relative yields and for comparison with the literature. Finally, the interpretation of these results is given and implications are drawn for the theoretical model.

Though the helium spectra must be regarded as unreliable, the general shape of the spectra does reflect an evaporation-like phenomenon. The cross sections rise to a maximum and then fall off exponentially with increasing energy. This qualitatively fits the picture discussed previously of evaporation of nuclear fragments from a hot Fermi gas. The peak ought to be characteristic of the nuclear coulomb barrier, with the yield below the peak being the result of quantum mechanical tunneling through the potential well. The measured spectra show qualitatively these general features, but the details of the spectra should be considered unreliable. That is, the location of the peaks in the spectra and slopes of the spectra at energies above and below the peak are uncertain. Also, the cross sections at 30° are thought to be too low since they are below the 90° data.

The computer code calculations gave smaller cross sections for all species than are indicated by the 90° data which ought to have a more reliable absolute normalization. This is the case for each of the targets, though the discrepancy becomes less severe as the mass of the target increases. The results of the computer code also show a characteristic coulomb barrier in the case of aluminum in Fig. 5.12 and nickel in Fig. 5.26. These spectral peaks are at approximately 1.37 MeV/amu and 2.8 MeV/amu, respectively, for

the 30° calculations. The code also shows a flatter fall-off of cross section at higher energy than does the data for each target.

Data from the literature also show this slower fall-off. For a carbon target, data exist from G. D. Westfall, et al.³⁸ for ^4He at 2.1 GeV and 90°. The slope of these data agrees well with the code and gives a higher cross section than the experiment and code gave at 800 MeV. This is as expected for higher excitation energies. J. P. Alard, et al.³⁹ have reported similar cross sections for 600 MeV protons at 90°, and these data appear substantially below the data and code predictions plotted in Fig. 5.2. Westfall, et al.³⁸ also report ^4He cross sections for 4.9 GeV protons on aluminum at 90°. Again, the slope of the experimental cross section at higher energies agrees well with the code and the cross sections appear to peak at nearly the same energy. Cross sections for ^4He from ^{58}Ni and ^{64}Ni at 1.0 GeV and 60° have been measured by E. N. Volnin, et al.,⁴⁰ and the ^{58}Ni results are shown in Fig. 5.26. Similar measurements at 660 MeV and 90° by V. I. Bogatin, et al.⁴¹ are also plotted. These data would all appear to be in fairly good agreement with the present experiment and the code except that the high energy fall-off of this experiment is, again, steeper than either the code or the other experimental measurements from the literature. The code, in this instance, predicts the flattest fall-off. The steeper fall-offs of the measured cross sections above 3 MeV/amu in this experiment are the result of the problem discussed earlier with determining the efficiencies for detecting these particles. Moreover, the software threshold on the ΔE signal discriminated against these lightly ionizing particles. Observations regarding the ^3He spectra are substantially the same as those for the ^4He data.

The computer code determined separately the production cross sections for ^3He and ^4He from evaporation and recoil. Only in the case of the carbon

target was there a significant contribution of ^4He recoils to the total spectrum, and even these did little to affect the overall shape of the spectrum.

The lithium spectra are considered to be much more reliable. The data at 30° , though still substantially influenced by the lower efficiency at this angle, gave cross sections higher than at 90° , as was expected. The fitted curves to the 90° data for each target shown in Figs. 5.39 through 5.41 indicate some characteristics of evaporation spectra. In these instances the peaks in the spectra are at higher energies for the more massive targets as would be expected for their larger coulomb barriers. The peak for ^6Li from the carbon target is near 1 MeV/amu, for aluminum near 2 MeV/amu, and for nickel near 2.25 MeV/amu. The lithium spectra from carbon would appear to be least evaporation-like. In fact, the ^7Li spectrum looks very much like the recoil spectra of the more massive products.

The code, not accounting for evaporations of lithium nuclei, gave more steeply sloped spectra and substantially underestimated the cross section at the higher energies for the carbon target and overestimated throughout. The three lowest energy data points at 30° for both ^6Li and ^7Li are probably excessively high as a consequence of background subtraction problems. Westfall, et al.³⁸ give cross sections for all lithium isotopes together from a carbon target for 2.1 GeV at 90° . These data are plotted in Fig. 5.3. Though these data show a steeper slope, more in line with the predictions of the code, they are not very different from the data of this experiment. The higher cross section at 2.1 GeV might be expected, since higher excitation energies would result, which increase the likelihood of lower mass recoil nuclei and the evaporation of more fragments. The lithium data for the nickel target, displayed in Figs. 5.27 and 5.28, show very flat spectra for the 90° data. The ^6Li spectrum is especially flat. Also, these spectra are nearly

ten times smaller than the spectra from the other two targets. The 30° data shows an increasing cross section with energy. This feature is not considered reliable because of the background subtraction problem noted earlier for nickel products with low event rates. The two lowest energy data points for ^6Li and ^7Li at 90° are probably also unreliable due to background considerations. Data from E. N. Volnin, et al.⁴⁰ for ^{58}Ni at 1.0 GeV are also presented in Figs. 5.27 and 5.28 for ^6Li and ^7Li . The agreement is quite good, though the relative magnitudes of the two sets of data might be expected to be the reverse of that shown.

The spectra of fragments with Z greater than three all appear to be more characteristic of recoils or residual nuclei. One exception appears to be ^7Be from the nickel target. In the following discussion some characteristics and trends of the data for these higher mass products are noted. The 30° and 90° spectra are qualitatively the same, with the 30° yield being somewhat higher than at 90° . The exception to this is the nickel data, where the low energy fragments have substantially lower cross sections at 30° than at 90° . These low energy data at 30° are, again, suspect for fragments less massive than ^{12}C . This is the result of the aforementioned background problem. Figures 5.37 and 5.38 showing the nitrogen and oxygen fragments, respectively, are not subject to background subtraction, and they show little angular disparity. However, the 30° cross sections are slightly lower. Also, the ^{11}C and ^{13}C spectra at 30° shown in Figs. 5.35 and 5.36 are much flatter than the 90° data.

The computer code showed similar weak angular dependence for the carbon and aluminum targets. No differential cross sections are plotted from the code for the nickel target as there was insufficient or nonexistent yield of these more massive products.

Westfall et al.³⁸ give experimental cross sections at 90° for several other heavy fragments from a carbon target bombarded by 2.1 GeV protons. The ⁷Be spectrum reported by these authors and plotted in Fig. 5.5 agrees well with this experiment, but shows somewhat higher values at low energy. The same can be said of the combined ⁹Be and ¹⁰Be data plotted in Fig. 5.7. The combined boron data of Westfall et al. plotted in Fig. 5.9 are also in good agreement, as is the combined carbon data plotted in Fig. 5.10. These same authors report spectra of fragments from aluminum bombarded by 4.9 GeV protons. Their spectra are steeper and their cross sections are larger than those found at 800 MeV. The nitrogen and oxygen spectra do have nearly the same slopes at the two energies, while the 4.9 GeV data show higher cross sections. The energy spectra measured at these two energies seem to corroborate each other nicely.

Given the weak angular dependence of the cross sections, the comparison of the spectra for species of a given target and between targets will be confined to the data at 90°. Fits of these data can be found for each target in Figs. 5.39 through 5.41. The differential cross sections of fragments from the carbon and aluminum targets each fall-off exponentially, while the nickel products, except ⁷Be and ⁹Be, each show some curvature in the semilogarithmic plots. The spectra of products from nickel each become increasingly flatter with increasing energy. The exceptions are ⁹Be, which shows a simple exponential fall-off, and ⁷Be, which, again, resembles the evaporation spectra of lighter fragments. This change in appearance for the more massive nickel target can be understood in terms of the theoretical model. These recoil products are the result of many successive evaporations, the final product having been reached by numerous paths from the highly excited initial nuclei left from the cascade stage. The spectra, as a whole, are superpositions of many recoil spectra representing many different

evaporation pathways. Also, each evaporation changes the coulomb barrier and nuclear temperature for succeeding evaporations. The same recoil product from either of the two lighter targets can be achieved with fewer evaporations, and so, the spectra are less complex.

The relative yields of a given fragment from the three targets will be discussed more fully below in terms of their total cross sections, but it is apparent that the nickel yields are much less than the yields from the two lighter targets. This is not surprising since the masses of the fragments detected in the experiment are far removed from the masses of the target nickel nuclei. The excited nucleus is likely to have de-excited to a stable state long before the recoil product has become as light as the fragments measured here. The ^7Be spectrum from nickel has much the same shape as the lithium spectra. This might indicate some evaporation of this aggregate from the nickel nucleus. The apparent peak of this spectrum is at about the same energy as is the ^7Li peak, though it would be expected to be slightly higher as a consequence of the larger coulomb barrier. The slopes of the cross sections for the same products from carbon and aluminum show the aluminum cross sections to be flatter. Note, for example, that the ^9Be spectrum from carbon is much steeper than is the same spectrum from aluminum.

The following discussion is confined to comparisons of the carbon and aluminum data to the computer code. The spectra at 90° predicted by the code for the higher mass fragments show a general tendency to become flatter than the experimental spectra as the product mass increases. In these cases the code overestimates the production of the highest masses at higher energy. The disparity is not great for Be isotopes from carbon and, in fact, in Fig. 5.5 the ^7Be spectrum from the code is actually slightly steeper than it is from the data. For the aluminum target, in those instances where the code gave sufficient yield to plot differential cross sections, the code does

quite well up to the boron isotopes and ^{11}C , but the trend for more massive products is for flatter spectra from the code than from the experiment, with ever increasing overestimation of the cross sections at higher energies.

Table 1 shows the results of integrating the differential cross sections at 90° from zero to 25 MeV for each of the species detected. In each case curves fitted to the data were extrapolated back to zero energy for the integration. These results were then multiplied by 4π to give a number representative of a total cross section. These pseudo total cross sections are of some value for comparisons with data in the literature and for comparisons of the relative yields of various products. Figure 5.42 displays the pseudo production cross sections measured for each of the fragments from each of the targets. Similarly, the computer code differential cross sections were integrated over the same range of energy and multiplied by 4π . The cross sections are displayed in Table 1 as well as in Fig. 5.43. Finally, Table 1 has ratios of the cross sections from experiment and code. Figure 5.44 shows these same ratios plotted for each fragment and target to facilitate comparison. Only limits are given for the cross sections of many of the nickel products since no yield of these products was given by the code.

The experiment shows the cross section for the light fragments up through ^7Li to be greater for the aluminum target than for the carbon. For all other fragments this is reversed. The helium cross sections from the nickel target are comparable to those for carbon and aluminum, but for lithium they are very much lower. The higher mass fragments have cross sections lower in most instances for the nickel target than for the lighter targets. For beryllium, however, the cross sections are very close to those of carbon and aluminum. Figure 5.43 shows the same trends for the carbon and aluminum cross sections as calculated from the theoretical code. However,

TABLE 1.--Experimental and Theoretical Cross Sections

	Carbon			Aluminum			Nickel		
	Exp. (mb) ±20%	Code (mb)	Ratio	Exp. (mb) ±20%	Code (mb)	Ratio	Exp. (mb) ±20%	Code (mb)	Ratio
³ He	50.89	11.34	4.49	65.97	28.78	2.29	52.78	33.65	1.57
⁴ He	218.65	110.59	1.98	407.65	141.91	2.87	286.41	238.76	1.20
⁶ Li	9.71	13.10	0.74	8.89	2.09	4.25	0.65	<.005	>131
⁷ Li	11.10	9.11	1.22	10.48	1.43	7.33	0.61	<.005	>120
⁷ Be	4.80	7.68	0.63	3.22	0.59	5.42	3.63	<.005	>726
⁹ Be	2.32	5.29	0.44	1.51	1.92	0.79	1.29	<.005	>258
¹⁰ Be	1.18	1.73	0.68	0.94	0.16	5.99	0.86	<.005	>172
¹⁰ B	6.40	20.48	0.31	2.07	1.85	1.12	2.86	<.005	>555
¹¹ B	6.32	31.57	0.20	3.84	1.97	1.95	1.42	<.005	>245
¹¹ C	3.15	24.82	0.13	1.53	1.07	1.43	1.42	<.005	>284
¹² C	---	---	---	4.65	7.88	0.59	1.48	<.005	>296
¹³ C	---	---	---	3.35	7.96	0.42	1.08	.037	29.30
N	---	---	---	8.03	26.52	0.30	1.65	.133	12.41
O	---	---	---	5.79	23.58	0.25	1.28	.189	6.78

Fig. 5.42.--Experimental Partial Production Cross Section for All Fragments

Fig. 5.43.--Theoretical Partial Production Cross Sections for All Fragments

Fig. 5.44.--Ratios of Experimental and Theoretical Partial Production Cross Sections for All Fragments

the code gave much larger ratios of carbon target to aluminum target cross sections than those given by the experiment. The predicted yields of fragments from nickel given by the code are also much lower than the measured yields. In most instances no heavy fragments were predicted by the code and only an upper limit could be assigned the cross sections.

The ratios of experimental and theoretical cross sections shown in Fig. 5.44 indicate that the code underestimates the helium cross sections from carbon and makes progressively worse overestimations for fragments more massive than lithium. This same trend is also seen for the aluminum target except that the code makes progressively larger underestimations throughout the ^7Be isotope. The code makes a slight overestimation for ^9Be , but underestimated ^{10}Be . The boron isotopes and ^{11}C are only slightly underestimated, but the trend for more massive products is for the code to make progressively worse overestimations of the yield. The code does a fairly good job of estimating the helium cross sections from nickel, but it grossly underestimates all the other fragment cross sections as noted earlier.

The implications of the aforementioned trends for the theoretical computer calculations are that, most likely, not enough excitation energy is being left by the code in the residual nuclei from the cascade stage of the reaction. If more energy were available for evaporation, higher yields of such products as ^{12}C , ^{13}C , N, and O from aluminum would be expected from the code. Similarly, some yield of lighter recoils from nickel would have a better chance of occurring since these can only be achieved after many successive evaporations. Finally, higher energy depositions in the recoil nuclei would improve the codes overestimation of those products with masses near that of the carbon target nucleus. This would be achieved since these relatively high mass recoils would necessitate further evaporations in order

to complete their de-excitation. This enhances the yield of lower mass fragments while diminishing the yield near the target mass.

Since the code uses experimentally derived cross sections for the nucleon-nucleon collisions in the cascade stage, it is unlikely that excessive energy is being removed by nucleons. A more likely explanation is that the nucleus has been treated as being more transparent to pions than is the case. If pions were allowed to take away more energy from the excited nucleus during the cascade stage of the code than they physically do, then the code might be expected to make the misestimations discussed above.

The observed discrepancies between the code and experiment are best accounted for by the picture given above. That is, insufficient energy deposition left over from the cascade stage for evaporation. Insufficient energy deposition is the likely consequence of the nucleus being made too transparent to pions. Though no other mechanism would so neatly account for all of the disagreements between code and experiment, there is no evidence that some other competing processes might not also be contributing to the experimental yield. Though the yields of the heavier mass fragments from nickel show spectra characteristic of multiple successive evaporations, some of these products could be partially the result of fission or evaporation of nuclear aggregates more massive than ${}^4\text{He}$. In fact, the lithium spectra from aluminum and nickel and the ${}^7\text{Be}$ spectrum from nickel show some evaporation-like characteristics.

This experiment has been successful in measuring the differential production cross sections of very short-ranged spallation products. The results of these measurements have shown some possible inadequacies of the theoretical cascade-evaporation codes. The results suggest that an improvement in the cascade code might be made by reducing the transparency of the struck nucleus to pions produced in the cascade. The evaporation code might

also be improved by incorporating evaporation of nuclear aggregates more massive than ${}^4\text{He}$. Finally, the very thin and fast detectors developed for the experiment have performed excellently for heavily ionizing ions.

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REFERENCES

1. N. Metropolis, R. Bivins, M. Storm, A. Turkevich, J. M. Miller, G. Friedlander, Phys. Rev. 110, 185 (1958).
2. N. Metropolis, R. Bivins, M. Storm, J. Miller, G. Friedlander, A. Turkevich, Phys. Rev. 110, 204 (1958).
3. I. Dostrovsky, P. Rabinowitz, R. Bivins, Phys. Rev. 111, 1659 (1958).
4. I. Dostrovsky, Z. Fraenkel, and G. Friedlander, Phys. Rev. 116, 683 (1959).
5. Hugo W. Bertini, Phys. Rev. 131, 1801 (1963).
6. Hugo W. Bertini, Phys. Rev. 188, 1711 (1969).
7. Hugo W. Bertini, Phys. Rev. C1, 423 (1970).
8. Hugo W. Bertini, Phys. Rev. C6, 631 (1972).
9. K. Chen, Z. Fraenkel, G. Friedlander, J. R. Gover, J. M. Miller, and Y. Shimamoto, Phys. Rev. 166, 949 (1968).
10. K. Chen, G. Friedlander, G. D. Harp, and J. M. Miller, Phys. Rev. C4, 2234 (1971).
11. G. D. Harp, K. Chen, G. Friedlander, Z. Fraenkel, and J. M. Miller, Phys. Rev. C8, 581 (1973).
12. G. D. Harp, Phys. Rev. C10, 2387 (1974).
13. J. N. Ginocchio, Phys. Rev. 17C, 195 (1978).
14. Ken Kikuchi and Mitsuji Kawai, Nuclear Matter and Nuclear Reactions (North-Holland Publishing Co., Amsterdam, 1968), Ch. 5.
15. F. S. Goulding and B. G. Harvey, LBL-2952 Preprint (1974).
16. Technical Application Note on the Bendix Chevron Channel Electron Multiplier Array.
17. V. M. Agronovich, D. K. Daukeev, Yu. V. Konobeev, and S. Yu. Lebedev, Soviet Physics JETP 30, 220 (1970).
18. L. C. Northcliffe and R. F. Schilling, Nucl. Data Tables 7 (1970).

19. E. L. Bell, *Rev. Mod. Phys.* 44, 465 (1972).
20. A. L. Lodhi and D. Powers, *Phys. Rev. A* 10, 2131 (1974).
21. Rita K. J. Palmer, *J. Phys. B* 7, 384 (1974).
22. J. Williamson and D. E. Watt, *Phys. Med. Biol.* 17, 486 (1972).
23. P. D. Bourland and D. Powers, *Phys. Rev. B* 3, 3635 (1971).
24. P. D. Bourland, W. K. Chu, and D. Powers, *Phys. Rev. B* 3, 3625 (1971).
25. J. Neufeld, *Phys. Rev.* 96, 1470 (1954).
26. N. Bohr, *Egl. Danske Videnskab. Selskab, Mat.-Fys. Medd.* 18, No. 8. (1948).
27. E. Fermi, *Phys. Rev.* 57, 485 (1940).
28. W. F. G. Swann and J. Franklin, *Inst.* 226, 598 (1938).
29. I. S. Dmitriev and V. S. Nikolaev, *Soviet Physics JETP* 20, 409 (1965).
30. V. S. Nikolaev and I. S. Dmitriev, *Phys Letters* 28A, 277 (1968).
31. L. C. Northcliffe, *Ann. Rev. Nucl. Sci.* 13, 67 (1963).
32. E. Serber, *Phys. Rev.* 72, 1114 (1947).
33. V. F. Weisskopf, *Phys. Rev.* 52, 295 (1937).
34. M. L. Goldberger, *Phys. Rev.* 74, 1268 (1948).
35. S. J. Sternheimer and E. M. Lindenbaum, *Phys. Rev.* 105, 1874 (1957).
36. S. J. Sternheimer and R. M. Lindenbaum, *Phys. Rev.* 109, 1723 (1958).
37. S. J. Sternheimer and R. M. Lindenbaum, *Phys. Rev.* 123, 333 (1961).
38. G. D. Westfall, R. G. Sextro, A. M. Poskanzer, A. M. Zebelman, G. W. Butler, and E. K. Hyde, *Phys. Rev. C* 17, 1368 (1978).
39. J. P. Alard, A. Baldit, R. Brun, J. P. Costilhes, J. Dhermain, J. F. Argeix, L. Frayssé, J. Pellet, G. Roche, and J. C. Tjmain, *Nuovo Cimento* 30A, 320 (1975).
40. E. N. Volnin, G. M. Amalsky, D. M. Seleverstov, N. N. Smirnov, A. A. Vorobyov, and Yu. P. Yakovlev, *Phys. Lett.* 55B, 409 (1975).
41. V. I. Bogatin, V. F. Litvin, O. V. Lozhkin, N. A. Perfilov, and P. Yakovlev, *Nucl. Phys.* A260, 446 (1976).

APPENDIX

THE CHARGE LOOK-UP TABLES

The AL version E/M look-up tables generated for heptane from the elemental stopping powers of Northcliffe and Schilling proved to be inadequate at low values of E/M. What follows is a description of a computer code written to generate range-energy relationships for the ions of interest, which could then be used as input to a second code that could generate new look-up tables.

The range of an ion with energy E can be expressed as a Taylor's expansion in the following way,

$$R(E) = R_0 + \sum_{n=1}^3 A_n (E-E_0)^n . \quad (A.1)$$

Here, E_0 is the energy about which the expansion is to be made, and the A_n are the expansion coefficients. The thickness of the gas in the ionization chamber, G, can be written as the difference in the range of an ion before and after the energy loss, ΔE , experienced in the gas volume

$$G = R(E) - R(E-\Delta E) . \quad (A.2)$$

Written out explicitly, one has

$$G = \sum_{n=1}^3 A_n ((E-E_0)^n - (E-\Delta E-E_0)^n) \quad (A.3)$$

and, upon taking the derivative with respect to E,

$$\frac{dG}{dE} = 0 = \sum_{n=1}^3 A_n (n(E-E_0)^{n-1} - n(E-\Delta E-E_0)^{n-1} (1 - \frac{\Delta E}{dE})) . \quad (A.4)$$

The second derivative gives an additional equation,

$$0 = \sum_{n=1}^3 A_n (n(n-1)(E-E_0)^{n-2} - n(n-1)(E-E-E_0)^{n-1}) (1 - \frac{d\Delta E}{dE})^2 + n(E-\Delta E-E_0)^{n-1} \frac{d^2 \Delta E}{dE^2} . \quad (A.5)$$

These last three equations can be solved for the coefficients A_n by matrix algebra. A simplification keeps only the A_1 and A_2 terms, leading to two equations as follows. Choosing to do the expansion about the energy of the ion as it enters the gas, one gets the following equations by setting $E = E_0$

$$G = A_1 \Delta E - A_2 (\Delta E)^2 \quad (A.6)$$

and

$$0 = A_1 \left(\frac{d\Delta E}{dE} \right) + 2A_2 \Delta E \left(1 - \frac{d\Delta E}{dE} \right) . \quad (A.7)$$

The reciprocal of the coefficient A_1 is representative of the stopping power of the ion in the gas volume. The calculated stopping power is correlated to the ion energy as it enters the gas, but it is a grosser approximation for low velocity particles. This is true because a greater percentage of the initial energy will be lost for these ions and, hence, the true stopping power will vary over a greater range during the traversal of the gas. Solving for the stopping power one gets

$$\frac{dE}{dx} = \frac{1}{A_1} = \frac{\Delta E}{G} \frac{(1 - \frac{1}{2} \frac{d\Delta E}{dE})}{(1 - \frac{d\Delta E}{dE})} . \quad (A.8)$$

This algorithm was used in the manner described below to calculate stopping

power, ΔE , could then be integrated to obtain the energy loss versus E/M relation. The computer code also solved the matrix equation obtained from the three eqs. (A.3) through (A.5) while retaining the A_2 terms. This method proved to be too sensitive to second derivative fluctuations in the raw data, even after attempts had been made to smooth that data by fitting with polynomials.

In order to obtain the derivatives required in the stopping power calculation, it was necessary to fit the ΔE versus E/M data points read from the scatter plots with polynomials. In this way one could also determine the energy loss at an arbitrary value of E/M from the fitted curve. To a first approximation E/M could be calculated directly from the time-of-flight measurement between the T_1 and T_2 detectors. Such E/M data was then adjusted to account for the deadlayer material preceding the gas volume. Before entering the gas the ion passed through the T_2 foil and the front window of the ionization chamber, W_1 . The energy loss in the deadlayers was assumed to be proportional to the loss in the gas, so that the adjusted E/M was given by

$$(E/M)' = [(E/M)M - (\frac{T_2 + W_1}{G})] / E/M \quad (A.9)$$

The computer code fitted cubic polynomials to sets of five data pairs of the ΔE and adjusted E/M data by doing a least-squares-fit. New data were generated from these fits at the same values of E/M as those used in the Northcliffe and Schilling tables.¹⁸ Spline fits were then done on this data, which allowed one to calculate the first and second derivatives of the fits at arbitrary values of E/M . With these derivatives the stopping power was calculated using the two methods described above. As mentioned, the method employing the second derivative proved to be too sensitive to fluctuations in the data. The method employing the algorithm of Eq. (A.8) was most

equation (1), and it was this expression that was used in the interpolation to get the requisite range-energy tables.

The range-energy tables were used as input to a second computer code that generated the requisite look-up tables. The look-up tables consisted of calculated predictions energy losses in the ionization chamber over the desired range of E/M for each of the species being investigated. Actually, there was one table generated for each possible mass and then M values were calculated for all charges with that mass. The calculation of the energy loss was done by determining the difference in energy between the particle before and after traversing the gas volume of the detector. The particle energy, and consequently its range, was known as it entered the detector. Its range after emerging from the detector was less by the amount of the detector thickness. The energy corresponding to this range would be determined and used to calculate the energy deposition in the detector. Comparison of the calculated energy losses was made with measured losses over the entire range of E/M . This was done by making plots of the ratio of these two values of M versus E/M for each charge state. The experimental values were read directly from scatter plots of M versus E/M , as the scatter of data in these plots fell in easily identifiable bands for each charge. The best intrinsic charge resolution was achieved when the ratio approached unity over the entire range of E/M .