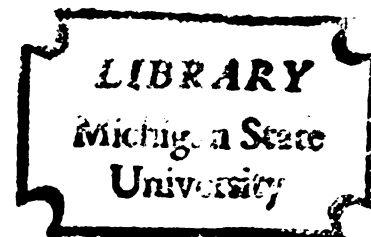


PROTON INDUCED REACTIONS ON ^{14}N AND ^{16}O AND
THE CREATION OF ELEMENTS LITHIUM,
BERYLLIUM AND BORON

Thesis for the Degree of Ph. D.
MICHIGAN STATE UNIVERSITY
HELMUT WOLFRAM LAUMER
1971



This is to certify that the

thesis entitled

Proton Induced Reactions on ^{14}N and ^{16}O
and the Creation of Elements Lithium, Beryllium
and Boron

presented by

Helmut Wolfram Laumer

**has been accepted towards fulfillment
of the requirements for**

Ph.D. degree in Physics

A handwritten signature in cursive script, reading "Sam M. Austin", written over a horizontal line.

Major professor

Date 4 November 1971

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ABSTRACT

PROTON INDUCED REACTIONS ON ^{14}N AND ^{16}O AND THE CREATION OF ELEMENTS LITHIUM, BERYLLIUM AND BORON

by

Helmut Wolfram Laumer

Measurements of cross-sections for production of masses 6 to 11 by proton spallation of ^{14}N and ^{16}O have been carried out. The proton energy range covered was 17 MeV to 42 MeV.

These cross-sections are indispensable in attacking an unsolved astrophysical problem, the origin of the light elements Li, Be and B. A number of theories have been proposed, and proton spallation of C, N and O is found to play a dominant role in several of them.

Two methods were employed in the cross-section measurements. For the main body of data collected particle identification was accomplished with a time-of-flight technique based on the narrow proton burst width of the M.S.U. Cyclotron. The particle energy measured with a silicon surface barrier detector and the particle flight time from target to detector yielded mass identification of spallation products. Angular distributions were collected and an integration over angle determined total cross-sections. For these measurements gas targets were used, contained in a specially designed gas cell with an exit beam window areal density in the range

50 $\mu\text{g}/\text{cm}^2$ to 130 $\mu\text{g}/\text{cm}^2$. As a check on the time-of-flight technique we measured ^7Be and ^{11}C cross-sections for proton spallation of ^{14}N at 21.7 MeV using radioactivation followed by γ -ray detection. Gas targets in a gas cell designed for γ -ray counting with the Ge(Li) detector were used. Good agreement was obtained for the cross-sections measured by the two methods.

A specific model for Li, Be, B production, proton spallation in the surfaces of stars, based on a theory by Bernas, is tested using the newly acquired cross-sections. A proton spectrum of the form $E^{-\gamma}$, based on solar flares, is considered. It is found that ^{14}N proton spallation is a large contributor to light element production in spite of the low ^{14}N abundance compared to ^{12}C and ^{16}O . To produce the ratio $^{11}\text{B}/^{10}\text{B} = 4$ as observed in the earth and in meteorites a value of γ low compared to that of proton spectra measured for solar flares is required. The ratio $^7\text{Li}/^6\text{Li} = 12.5$ as observed for earth and meteorites, on the other hand, can be produced only by proton spectra with improbably high values of γ . A depletion mechanism for ^6Li or alternate production mechanisms for ^7Li are the more likely explanations for this ratio.

PROTON INDUCED REACTIONS ON ^{14}N AND ^{16}O AND
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1. INTRODUCTION

1.1 Nucleosynthesis in Stars

One of the more spectacular successes of nuclear astrophysics is the explanation (CL68) of many of the features of the natural abundance curve of the elements. The correlation of nuclear properties of heavier elements with the observed abundances is so striking that the mechanisms for their production are quite well established. Figure 1 shows a relative abundance curve with regions labeled by their dominant production mechanisms in stars. During the lifetime of a star the fusion reactions in its interior fuse nuclei in an ascending sequence of mass. Hydrogen-burning converts hydrogen into ^4He , and if ^{12}C and ^{16}O are present these are converted largely to ^{14}N if the star's mass is large enough. Once the hydrogen fuel is exhausted the star contracts until the temperature at the center is high enough to overcome the coulomb barrier of $^4\text{He} + ^4\text{He}$, and the helium burning process begins. The major products are ^{12}C and ^{16}O , with ^{20}Ne and ^{24}Mg also perhaps possible (IB 66, TU 71). Once ^4He is also exhausted $^{12}\text{C} + ^{12}\text{C}$ and later $^{16}\text{O} + ^{16}\text{O}$ are expected to react, to form nuclei up to ^{32}S . The temperature necessary to burn the next most likely fuel, ^{24}Mg , is so high that (γ, p) , (γ, n) and (γ, α) reactions become dominant before it is ever reached. These reactions convert the products

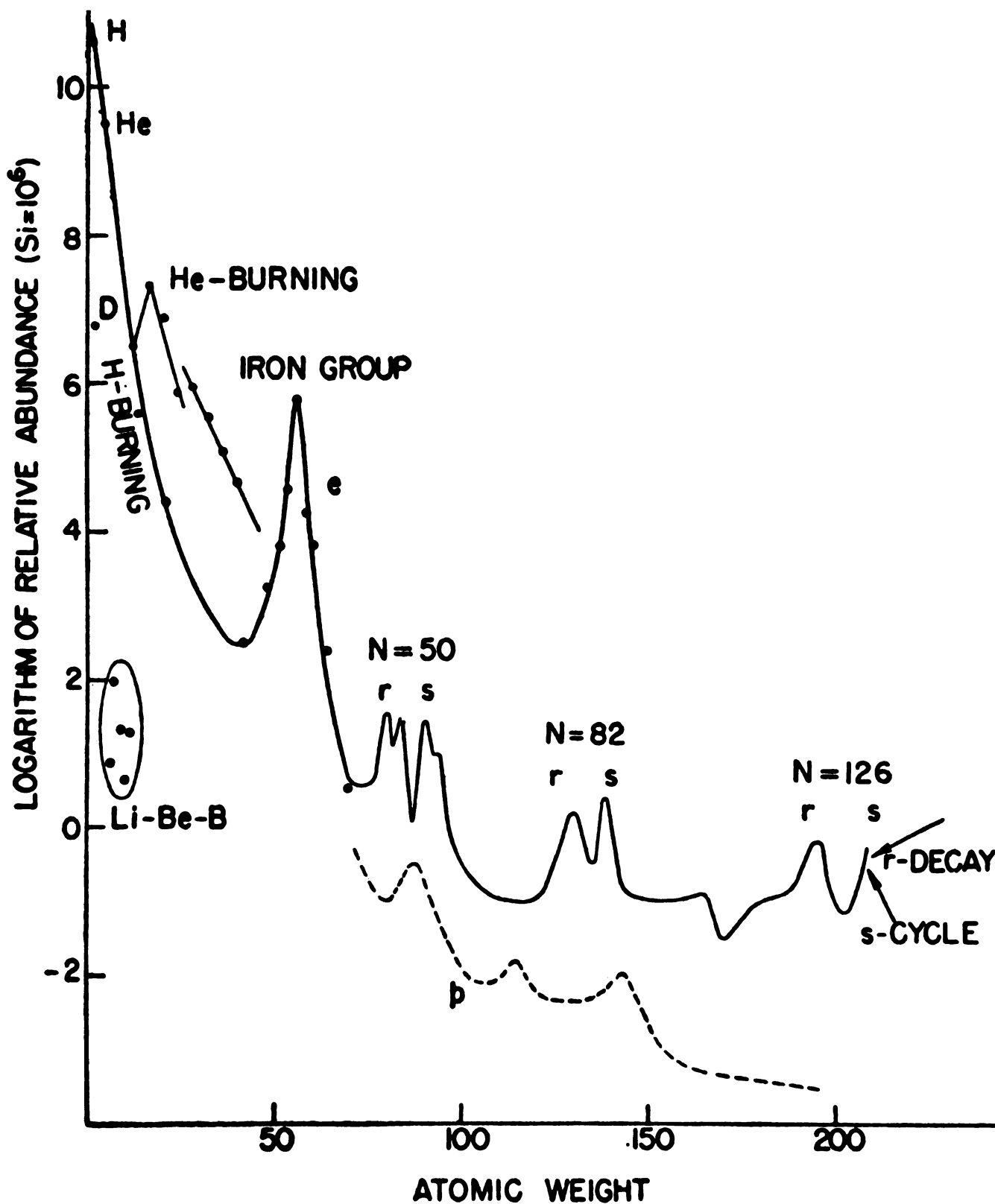
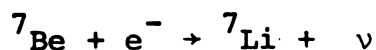
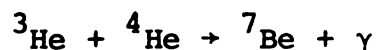
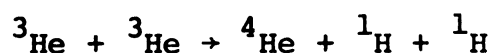
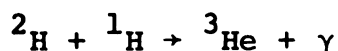
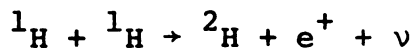


Figure 1. Curve of Relative Abundances From (BBFH 57) Based on Suess and Urey.

from the last burning stage, A near 28, to the more stable nuclei with A near 56. This last process is called silicon burning or photodisintegration rearrangement. Recent calculations (AC 70) show that explosive carbon, oxygen and silicon burning can give good agreement with observed abundances in the range $20 < A < 62$. At temperatures higher than necessary for silicon burning, the photodisintegration and net production of iron group nuclei becomes balanced. This is called the equilibrium or e process. The elements heavier than those of the iron peak are more abundant than expected from these processes. The mechanism for their production is neutron capture. Two processes, r (rapid) and s (slow), are postulated. In the s process there is time for β^- decay after (n, γ) reactions have produced a β^- unstable nucleus; a neutron capture chain climbing the valley of stability of the nucleidic chart is the result. In the r process fast neutron captures produce a highly β^- unstable, neutron rich nucleus near the neutron drip line. Subsequent β^- decay then leads to the resulting stable nucleus. There are some proton rich heavy isotopes which cannot conceivably be produced by the r or s process. Their abundances are considerably lower than those of isotopes accessible by the r or s process. Presumably (p, γ) and (γ, n) reactions on nuclei synthesized by the r or s process can account for the abundances. In Figure 1 the abundance of Li, Be, and B is seen to be anomalously

low compared to their neighbors. In the nuclear burning processes in stars described above, they are largely bypassed. They are also very fragile so if present or produced during hydrogen burning, (p, α) reactions quickly destroy them (BGRS 67). For example ^7Li can be produced in hydrogen burning by the reaction chain:



only to be destroyed by $^7\text{Li} + ^1\text{H} \rightarrow ^4\text{He} + ^4\text{He}$. As a result even the low abundance of Li, Be and B becomes difficult to explain. Spallation reactions on the more plentiful nuclei are the suggested (FBB 55) mechanisms for their production. In the case of ^7Li cosmological production is also a possibility (WFH 67).

1.2 Need for Cross Section Measurements

Since ^{12}C , ^{14}N , and ^{16}O are the most abundant of the nuclei heavier than Li, proton induced spallation of these targets is the process most likely involved in forming the light elements Li, Be and B (FBB 55). The reaction cross-sections for these targets are thus of great interest. While data for ^{12}C exist at most energies (DLA 70, AER 67), only a few cross-section measurements for ^{16}O above 100 MeV proton energy are available, and there was little data on

^{14}N until the recent ^{11}C and ^7Be cross-section measurements by M. Ephreffe and C. Seide (ES 71). The threshold region for light element production cross-sections is of special interest for several reasons. Theoretical calculations are most unreliable for this region, hence predictions valid at higher energies are of marginal value here. Proton spectra encountered in nature (FW 63) usually vary as a negative power of the energy, hence there are considerably more protons available for reactions at lower energies where in addition the cross-sections are also often larger than at high energies. Due to differences in threshold energies for their production, the formation ratios of isotopes vary most drastically in the threshold region; in view of the proton spectrum cited above, relative abundance calculations will be sensitive to these cross-sections.

1.3 Difficulty of Measurements

The sparse cross-section data for Li, Be, and B production is not due to lack of interest on the part of experimenters, but is the result of extreme experimental difficulty encountered. The most straightforward technique used in the past is radio-activation analysis. This is limited to radioactive products however and thus cannot yield all the cross-sections of interest. Mass spectrometry has also been employed in some measurements, but this technique is beset by difficulties such as sample contamination and variable sensitivity to isotopes; hence, it is very time consuming (see for example (YI 68)). Attempts have also been made (JU 70) to use emulsions; but contributions

to cross-sections from break up which leads to more than one free neutron could not be measured. The data collected also suffered from poor statistics.

1.4 Time of Flight Technique

The method used in my measurements is the time-of-flight technique reported in (DLA 70), as modified for application to gas cells. A collimation system limits the volume from which particles may reach an energy sensitive particle detector. By choosing a flight path which is long compared to the dimensions of this gas volume, particles can be assigned a flight time which in conjunction with the energy measurement determines the particle mass:

E = particle energy

t = flight time

D = path length

$$E = mv^2/2 = m \left(\frac{D}{t}\right)^2/2$$

$$\text{hence } m = \frac{2Et^2}{D^2} .$$

Angular distributions are obtained by integrating spectra over energy for each particular mass. An integration of a distribution over angle then yields the total cross-section for the mass.

It may seem that particle mass identification is insufficient since ^{11}B and ^{11}C , for example, cannot be distinguished. For the astrophysical application however the information is quite complete since only one isobar per mass number is stable in the region $6 \leq A \leq 11$. All other isobars

of the same A detected in our experiment decay to it on astrophysical time scales with two minor exceptions. The ^9C production threshold from ^{14}N is at a proton energy of 39 MeV. Since $^9\text{C}(\beta^+) ^9\text{B} + \text{p}(2\alpha)$ this does not lead to ^9Be . The production threshold of ^9C from ^{16}O is at 50 MeV proton energy, hence it cannot be produced in our accessible energy range. Although ^{10}Be does decay to ^{10}B , its half-life is 2.7×10^6 years; fortunately ^{10}Be production is low at least at the high proton energies measured (YBDFGB 68, 0.3 ± 0.2 mb for 135 MeV protons on ^{16}O). The threshold for its production from ^{14}N is 34 MeV, from ^{16}O it is 36 MeV. The time of flight technique does have the weakness that it fails for very low energy products. Since at 22 MeV proton energy ^7Be and ^{11}C are the only isotopes of $A=7$ and $A=11$ produced from spallation of ^{14}N , I performed a cross-section measurement based on their radioactive decay to check the time of flight technique; this is presented in chapter 5.

The MSU Cyclotron is particularly suited to make measurements with proton energies from 22 MeV to above 40 MeV. In this range the beam intensity needed (≈ 500 n amp), and narrow pulse width (0.2 n sec has been achieved) of beam bursts essential for the success of the time of flight technique can be routinely obtained. This energy range is also important for relevant theories of nucleosynthesis of LiBeB as pointed out above.

The experimental equipment used in the time of flight measurements is discussed in chapter 2. Chapters 3 and 4 treat data acquisition and reduction respectively. Chapter 5 contains the radioactivation-decay measurements and chapter 6 presents the major developments in astrophysical theories on the production of LiBeB . Conclusions and calculations based on the newly acquired cross-sections and pertinent to these theories are presented in chapter 7.

2. EXPERIMENTAL EQUIPMENT AND TECHNIQUES FOR TIME-OF-FLIGHT MEASUREMENTS

2.1 The M.S.U. Cyclotron Facility

The proton beam of the MSU cyclotron was used for all experiments. The time-of-flight technique depends most of all on the narrow beam burst width that can be achieved with this cyclotron. Widths as low as 0.2 nsec FWHM have been measured. The widths during our experiment have usually varied from 0.3 nsec to 0.5 nsec. The spacing between beam bursts depends on the frequency of the cyclotron RF and is therefore beam energy dependent. This spacing is 53 nsec at 42 MeV and 72 nsec at 22 MeV. As explained below (Appendix F) this spacing limits particle detection at low particle energy.

A schematic drawing of the beam transport and analyzing system is shown in Figure 2. The time-of-flight measurements were done in the large scattering chamber shown. Lately this is a 40 in. diameter chamber; in the early parts of the experiment a 35 in. diameter chamber was in its place. The irradiations for γ -ray counting were done in the small scattering chamber associated with the Enge split-pole-spectrograph because it allows faster access.

On-target-beam-spots were 0.030" to 0.050" wide by less than 0.1" high and beam currents from 300 to 800 namp were routinely obtained. Usually 3 to 4 μ amps were extracted with 100% efficiency from the cyclotron under these conditions

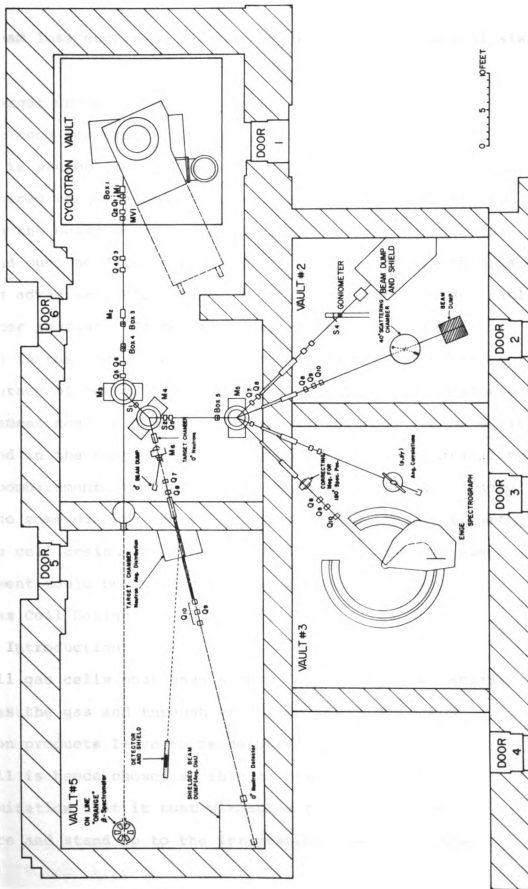


Figure 2. Schematic Drawing of the Beam Transport and Analyzing System.

with beam loss occurring at the various slits in the analysis system.

2.2 Target Choice

At room temperature N and O are gases, so if a solid target is wanted one must select some compound which contains the desired target elements as a constituent. The contribution to the observed yield due to the other elements in the compound must be determined however. The use of gas targets appears advantageous in this respect. They are also desirable for other reasons. Target thickness measurements for solid targets in the $100 \mu\text{g}/\text{cm}^2$ range are not easily performed to an accuracy of better than 10%. For gas targets a pressure measurement need only be made. Here 1% accuracy can be easily achieved in the range 0.1 to 1 atmospheres. Target stability under bombardment is also no problem for N and O gas. There are also some disadvantages encountered in using gas targets. The gas cell design described below minimizes them so the experiment could be carried out successfully.

2.3 Gas Cell Design

2.3.1 Introduction

All gas cells must have a thin foil or "window" which confines the gas and through which the beam enters and reaction products leave to be detected outside the cell. The foil is hence chosen as thin as possible subject to the limitation that it must withstand the required gas pressure and stand up to the irradiating beam. A common

foil used for gas cells is Kapton¹ available in 0.00025", 0.0005", or 0.001" thicknesses. For the relatively heavy, low energy reaction products which are to be detected in spallation of ^{14}N and ^{16}O , this still implies a large and unacceptable energy loss (see Appendix A). While a specially thin window must be used for these products, in our case it is a $30\text{ }\mu\text{g}/\text{cm}^2$ formvar film, Kapton is quite acceptable as proton beam window; the energy loss for a 22.0 MeV proton traversing a 1/2 mil foil is only 0.040 MeV.

2.3.2 Slit System Design

When measuring yields with solid (foil) targets, the volume from which reaction products originate is usually well defined. One need only use one aperture in front of the detector to fix the solid angle for particle acceptance. In gas cells reaction products can originate anywhere along the line segment joining the point of entrance and the point of exit of the bombarding beam. Since the nuclear debris from the gas cell wall is not what one wants to measure, an additional slit is needed to limit the volume from which particles may reach the detector.

For the time-of-flight technique the slit system must be carefully designed. In Figure 3 the acceptance angle determined by slits 1 and 2 is shown. The beam intersects the rays of angle β at points A1 and A2. Reaction products falling on the detector may originate from any point on

¹Available from E.I. Du Pont de Nemours, Wilmington, Delaware.

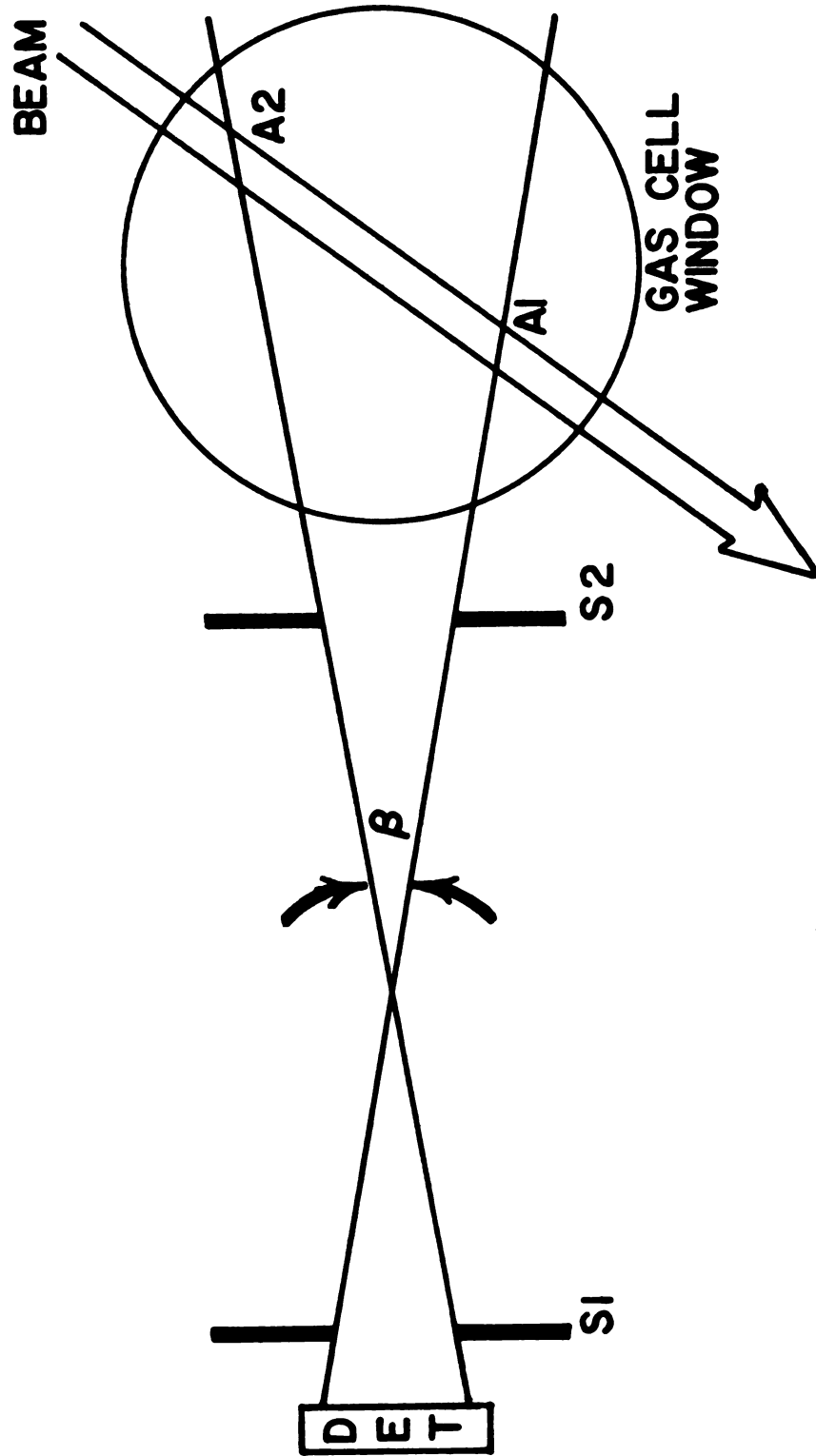
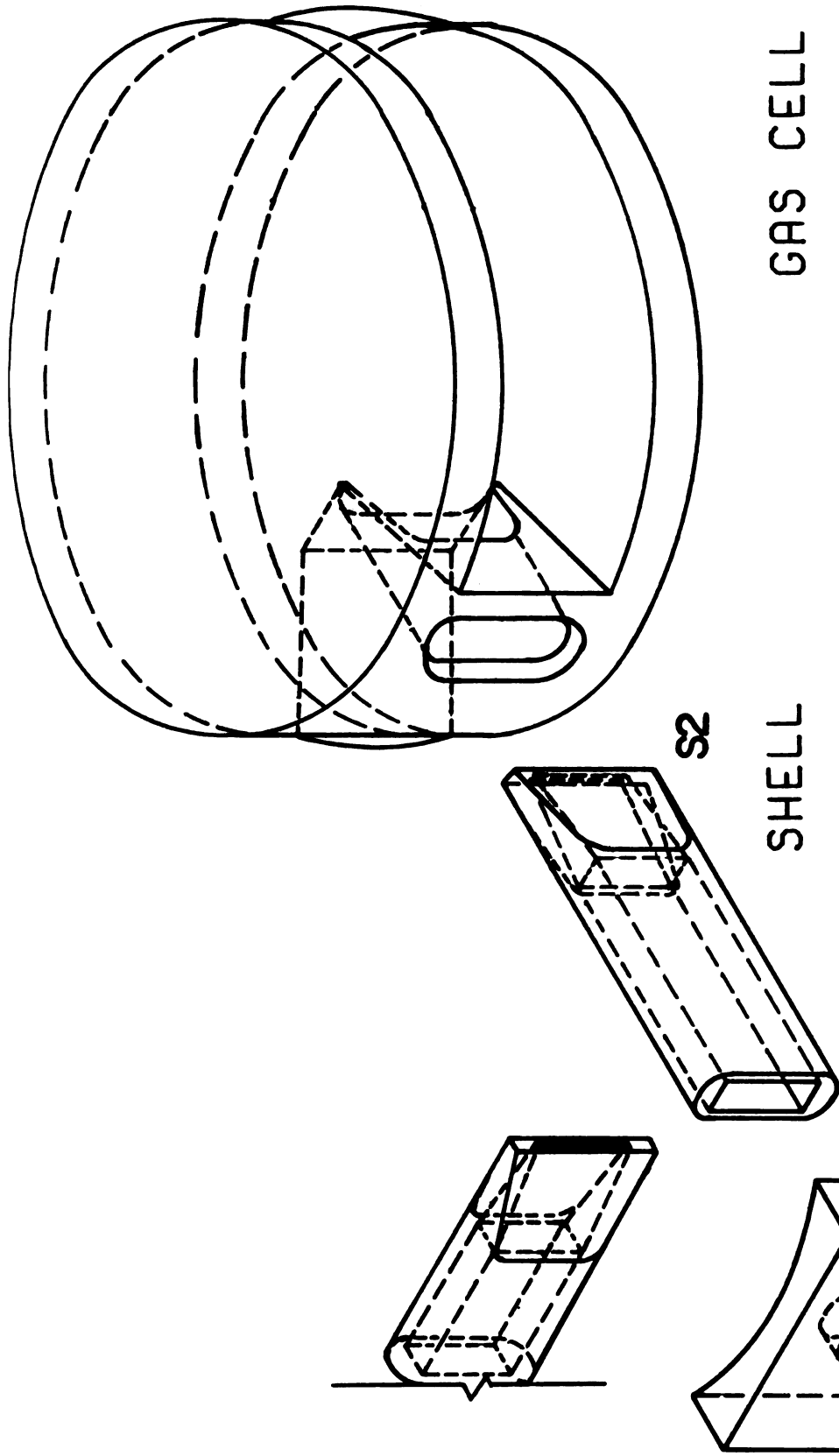


Figure 3. Schematic Drawing of a Gas Cell and its Slit System.

the line segment A1A2. This means that there is a range of flight distances. This manifests itself in terms of an uncertainty in the flight time of reaction products. In Appendix B the calculations relating the slit geometry to counting rate and flight time resolution are presented. The conclusions one can draw are that S2 should be as close to the origin of reaction products as possible. The width of S2 and the width of the beam are then equally critical as far as flight time resolution is concerned. Making S2 smaller than the width of the beam would gain little for flight time resolution but would lower the yield, an obvious disadvantage. The size of S1 is not as critical and is mainly determined by the active area of the detector. S1 represents the horizontal extent of the aperture in front of the detector. The vertical dimension of this aperture has even less effect on differences in flight path length. The dimensions of the aperture used were .125" wide x .25" high.

2.3.3 The Shell, Collimation Slit and Formvar Window Support

The above considerations led to the gas cell design shown in Figure 4. The important element is a cylindrical shell sliding in a keyway in the cell. The end of the shell closest to the beam acts as defining slit S2. It also supports a formvar film which acts as the cell exit window for the spallation products. Since S2 must be fixed with respect to the detector, and since S2 is rigidly secured to the gas cell, the slit, cell, and detector must rotate together when the detection angle is to be changed.



GAS CELL

S2

SHELL

O-RING

CLAMP

Figure 4. Gas Cell Design

The shell is milled in two parts which are then sweat-soldered together. The curved surfaces are milled last, after which the shell is polished. The lips at S2 are rounded by buffing. This ensures that the stresses causing rupture of the formvar window under pressure are better distributed. The slit end of the shell is also tapered so it can be moved as close to the beam as possible.

Reaction products lose energy not only in the formvar window but also in the gas they must traverse. Depending on the detection angle the shell is positioned to minimize this distance. At 1/10 atmosphere the density of N_2 is $125 \mu\text{g}/\text{cm}^3$. It would seem desirable to work with low gas pressures to minimize energy loss; however the yield and hence the time needed to perform the experiment is directly proportional to the gas pressure. Also background events are largely independent of gas pressure; this implies a minimum pressure for a successful experiment. For a nitrogen pressure of 25 torr and a $30 \mu\text{g}/\text{cm}^2$ formvar exit window we can obtain an average total exit areal density of $50 \mu\text{g}/\text{cm}^2$ at 90° and $130 \mu\text{g}/\text{cm}^2$ at 15° detection angle.

In order to avoid repeated mechanical adjustments of the shell, but to still minimize energy loss in the gas, we simply mounted the gas cell and slit system slightly off center on the scattering chamber table. As shown in Figure 5 table rotations between 15° (or 165°) and 90° can be carried out with one shell setting. The distance between the beam and the closest point of the shell is

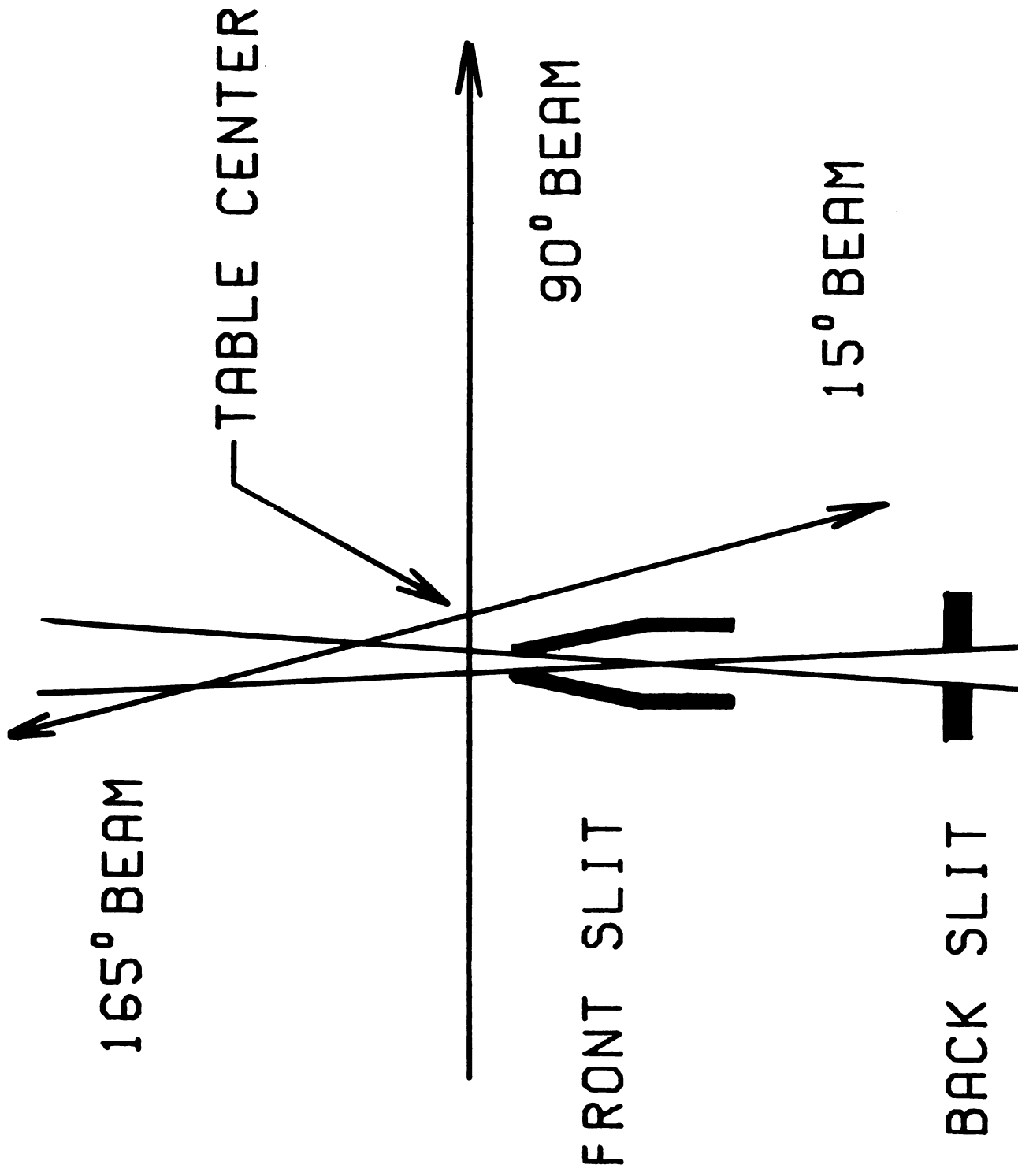


Figure 5. Schematic Drawing Showing Slit System - Table Center Geometry.

about constant and as a result practically minimum in-gas flight distance is achieved at all angles in this range.

The vertical extension of S2 is 0.750". Since the detector aperture is 0.250" high and the beam was always less than 0.1" high, this represents a big margin of safety for vertical alignment. The variation of the beam height with respect to the cell center was always less than $\pm 3/32$ " as seen by beam spot burns on the Kapton window.

The horizontal dimension of the shell was chosen to be 7/16" so S2 widths up to 1/4" could be accommodated.

2.3.4 Gas Cell Construction

The gas cell structure is made of brass. Two 5" disks were silver soldered to a spacer which had been milled with a keyway for receiving the shell. The spacer subtends 60° from the center of the cell. After silver soldering, the cell diameter was turned down to 4.75". A chamfer was then milled at the mouth of the keyway. This forms one surface of an O-ring vacuum seal; the other is the side of the sliding shell. The pressure needed for the seal is exerted with a clamp screwed to the body of the cell.

The geometry of the shell and the vacuum seal determine the minimum detection angle. This is the reason for the non-circular design of the shell. A tube of 1.125" diameter in a gas cell of the same diameter would allow a minimum detection angle near 20°, while for the actual design it is 10°.

A 0.25" Imperial Eastman vacuum fitting soldered into the top disk of the cell serves the double function of evacuation outlet and gas inlet. Kapton foil 0.0005" thick was bonded to the gas cell using the epoxy Ciba Araldite 502. The brass surface was prepared by light sanding or filing just prior to the epoxy application. At pressures up to 50 torr and beam currents up to 800 nano-amps the Kapton held up indefinitely.

2.4 Formvar Windows

Formvar ($\text{H}_{16}\text{O}_8\text{C}_4$)¹ is available in powder form. To cast formvar film a 2% solution by weight of formvar in 1, 2 Dichloroethane is prepared. A 6" diameter glass beaker is filled with distilled water (care must be taken that no soap residue is in the beaker, since the surface tension of the water would be reduced). A 14 B.S. gauge wire is dipped into the formvar solution and a line is drawn with the wire tip across the water surface. A thin layer of solution spreads on the water and within a few seconds the 1, 2 Dichloroethane evaporates, leaving a formvar film.

This film is lifted from the water with a square wire loop. The plane of the loop is held perpendicular to the water surface during the lifting process. A double layer of formvar clings to the loop and is transferred immediately to the slit end of the shell by passing the shell through

¹Available from Shawinigan Resins Corporation, Springfield 1, Mass.

the wire loop. This process is repeated until a formvar window of the desired thickness has been built up. Air drying for a few hours cures the formvar film. The drying may be speeded up by using an infrared heat lamp. Very thin wrinkle free formvar films are produced by the technique just described. To measure the average thickness of formvar film produced by the above technique, 44 double layers were cast and transferred to a 5/8" i.d. copper tubing. The energy loss of the 5.48 MeV alpha particles from an americium source was used to calculate the thickness. The electronics to process pulses suitable for a Nuclear Data 160 multi-channel analyzer was the same as for the energy signals for particle identification described under data acquisition and shown in Figure 7. The electronics was checked for linearity with test pulses, making sure $E=0$ corresponded to channel 0 of the ND 160. The 5.48 MeV peak centered in channel 587 shifted by 9.5 channels when the built up formvar film was introduced between the source and the silicon surface barrier detector. The calculation in Appendix C shows this represents an average thickness of $2.4 \pm 0.2 \frac{\mu\text{g}}{\text{cm}^2}$ double layer.

A $30 \mu\text{g}/\text{cm}^2$ formvar window over a 0.040" slit sustains a pressure of 25 torr for many hours. The films are weakened by the variable stress occurring during repeated pumping down to vacuum and letting up to air pressure.

2.5 Pressure Measurements

2.5.1 Equipment

The gas pressure was measured and monitored at first with a Wallace and Tierman Type FA 145PP12296 aneroid gauge, later with an oil manometer designed and constructed by Lolo Panggabean. It has a range of 135 cm of oil; each miniscus can be read to ± 0.5 mm, hence the net error is $\approx \pm 1$ mm for a pressure measurement. The oil used is the pump fluid Octoil¹. At 25°C its density is 0.983 g/cm³; its vapor pressure is 2×10^{-7} mm Hg.

A manifold interconnects gas cell, scattering chamber, manometer and target gas source. During data taking one side of the manometer is held at scattering chamber pressure (vacuum) while the other side is connected to the gas cell. During pump down all components are held at the same pressure, evacuation proceeds through the scattering chamber pumps.

2.5.2 Beam Heating

To calculate the target gas density, besides knowing the pressure, one must know the gas temperature. Since the beam loses energy as it traverses Kapton and gas, it is not obvious what the temperature of the irradiated volume is.

To obtain a rough estimate of how much the gas in the beam trajectory might be heated, the naive model described in Appendix D is considered; for our average operating conditions it predicts a temperature rise of $\approx 25^\circ\text{C}$ above

¹Octoil is manufactured by Consolidated Vacuum Corporation.

ambient gas temperature.

To experimentally check the effect and compare it to values given by the model, the beam was focused to produce a beam spot 0.025" wide, 0.045" high on the Kapton window. A cesium-iodide crystal mounted on a phototube was used to monitor the proton spectrum for scattering of 35 MeV protons from ^{20}Ne . The proton counts from the ground and first excited state were used to monitor the product of beam current and ^{20}Ne density. A 500 nano amp beam and a 100 nano amp beam were compared, results are given in Table 1.

TABLE 1. Beam heating comparison data.

Beam Current (nano amps)	Monitor Counts	Pressure (cm oil)	Integrated charge (10^{-7} coulombs)
500	152,277	53.35 ± 0.2	3375.4
100	4,494	53.10 ± 0.1	100.1

These data imply $T_{500}/T_{100} = 1.00 \pm 0.015$. The model predicts $T_{500}/T_{100} = 1.06$; the discrepancy is most likely due to more efficient gas mixing than postulated. To first order any error in charge integration is the same for both cases so the error in the ratio due to the pressure readings and total charge collected is negligible compared to the statistical error of 1.5% for the 100 nano amp beam measurement. To make sure the beam spot was of the same dimensions in both cases, slits near a beam antinode were used to cut the beam from 500 n amps to 100 n amps; this should not have influenced beam spot size which is determined by the object

slits.

2.6 Beam Integration

A 57" section of 4" diameter beam pipe served as Faraday cup for charge collection. The beam was dumped on an aluminum plug at the end of the pipe. The section was insulated from the scattering chamber by a 1.5" plastic ring. Charge integration was performed with an Elcor model A310B current indicator and integrator. Performance of the integrator was checked with a 1.35 volt mercury cell in series with a 1% 4.5 meg. ohm resistor. This test was performed both at the input to the integrator in the data room and at the Faraday cup. The maximum deviation between expected and observed total charge was 1.6%. The average deviation was less than 1%. Two successive 9 min calibrations were consistent to within 0.17%.

2.7 Particle Detectors

2.7.1 Spallation Product Detection

Particle energy was measured with silicon surface barrier detectors manufactured by Ortec. Thinner detectors have faster rise times, hence yield better timing pulses for low energy signals. For this reason thin detectors, 75 μ and 85 μ thick, were used for all proton beam energies below 40 MeV. At or above 40MeV a 150 μ detector was used for the ^{14}N target. Minimum detector thickness was set by the requirement that all spallation products heavier than mass 5 be stopped in the detector. A 250 μ detector placed behind the thin detector served as veto for particles not

stopped in the first detector. This was done to minimize computer processing time for uninteresting events.

To achieve best possible energy resolution, the detector was cooled by pumping alcohol cooled to near dry ice temperature through a copper yoke which held the detector. It was also usually overbiased by 50% to insure short collection times and hence achieve optimum timing signals. The energy resolution, checked with the 5.48 MeV α peak of an americium source, was always better than 40 keV FWHM. The detector holder, solid angle defining aperture, and gas cell are all mounted rigidly on a rail held in a block of aluminum which is provided with pins that fit precisely into positioning holes of the rotary scattering chamber table. This system assures reproducibility of geometry.

2.7.2 Proton Elastic Peak Monitor

To calculate the cross-section corresponding to an experimental yield measurement, one has to know both the integrated charge of the proton beam and the density of the gas target. A gas leak during a bombardment would present a difficult pressure monitoring problem. It is a common technique to use a monitor cross-section to integrate the product of gas density and beam intensity during a bombardment. The proton detector is set at a fixed angle and the proton energy spectrum is recorded. The number of events in the elastic peak for each bombardment represents the integration. The pressure must then be accurately known only for a calibration point (see Chapter 2, section 2.5.1).

MONITOR ELECTRONICS BLOCK DIAGRAM

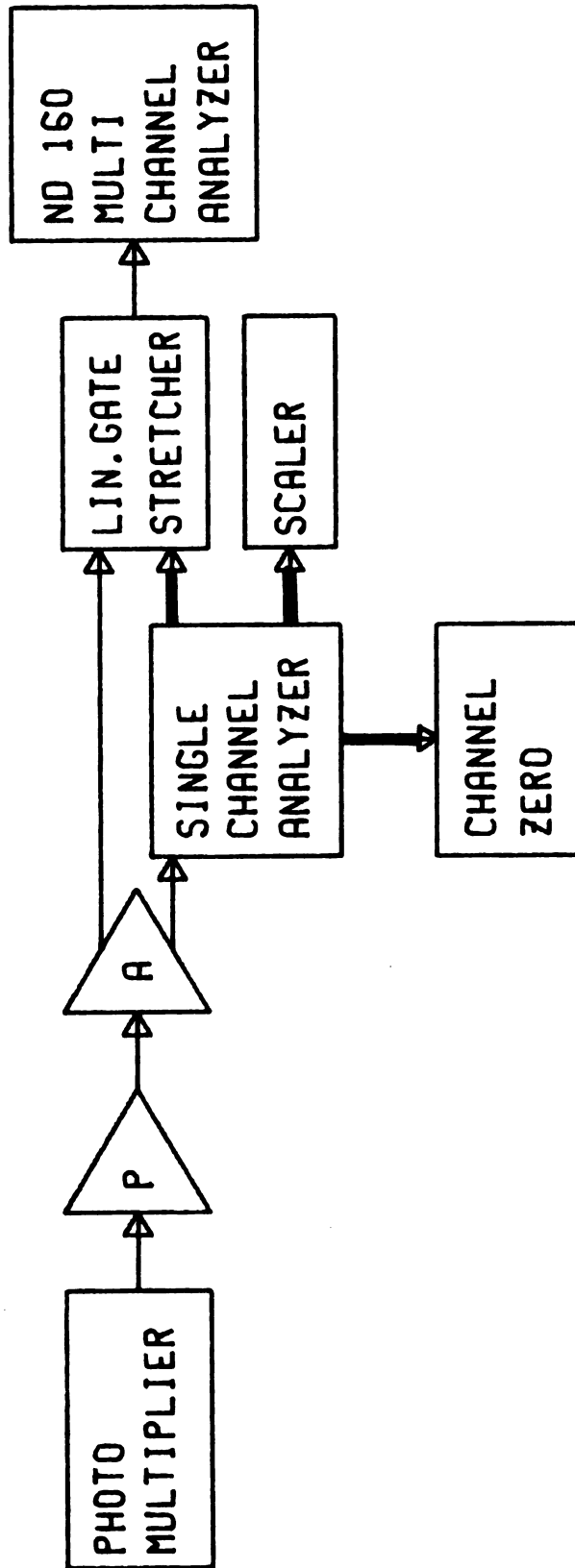


Figure 6. Monitor Electronics Block Diagram.

A cesium iodide crystal mounted on a phototube was used to monitor the proton spectrum. (This detector was designed and constructed by Larry Learn of the MSU Cyclotron Lab.) Figure 6 shows the electronics used to record the spectra. A single channel analyzer was set to accept only pulses from the elastically scattered proton peak. The proton spectrum was also collected in a Nuclear Data 160 multichannel analyzer so gain shifts in the photomultiplier could be detected and scaler counts could be corrected if necessary.

2.8 Time-of-flight Electronics

A schematic of the electronics configuration is shown in Figure 7. Table 2 identifies abbreviations, manufacturers, and model numbers.

Reaction products of interest are stopped in a silicon surface barrier detector, labeled E detector. It is connected by a 3ft, 22pfd/ft Microdot cable to a time-pickoff unit and then to a preamplifier. The time-pickoff in conjunction with a time-pickoff control derives a timing pulse from each energy pulse. This system employs leading edge timing. A time-to-amplitude converter (TAC) is started by this timing signal. The stop pulse is obtained from the cyclotron RF system.

To avoid the non-linear region of the TAC ($\approx 15\%$ of the 100 nsec range), it is desirable that the RF stop pulse occurs at least 25 nanoseconds after the start pulse. To

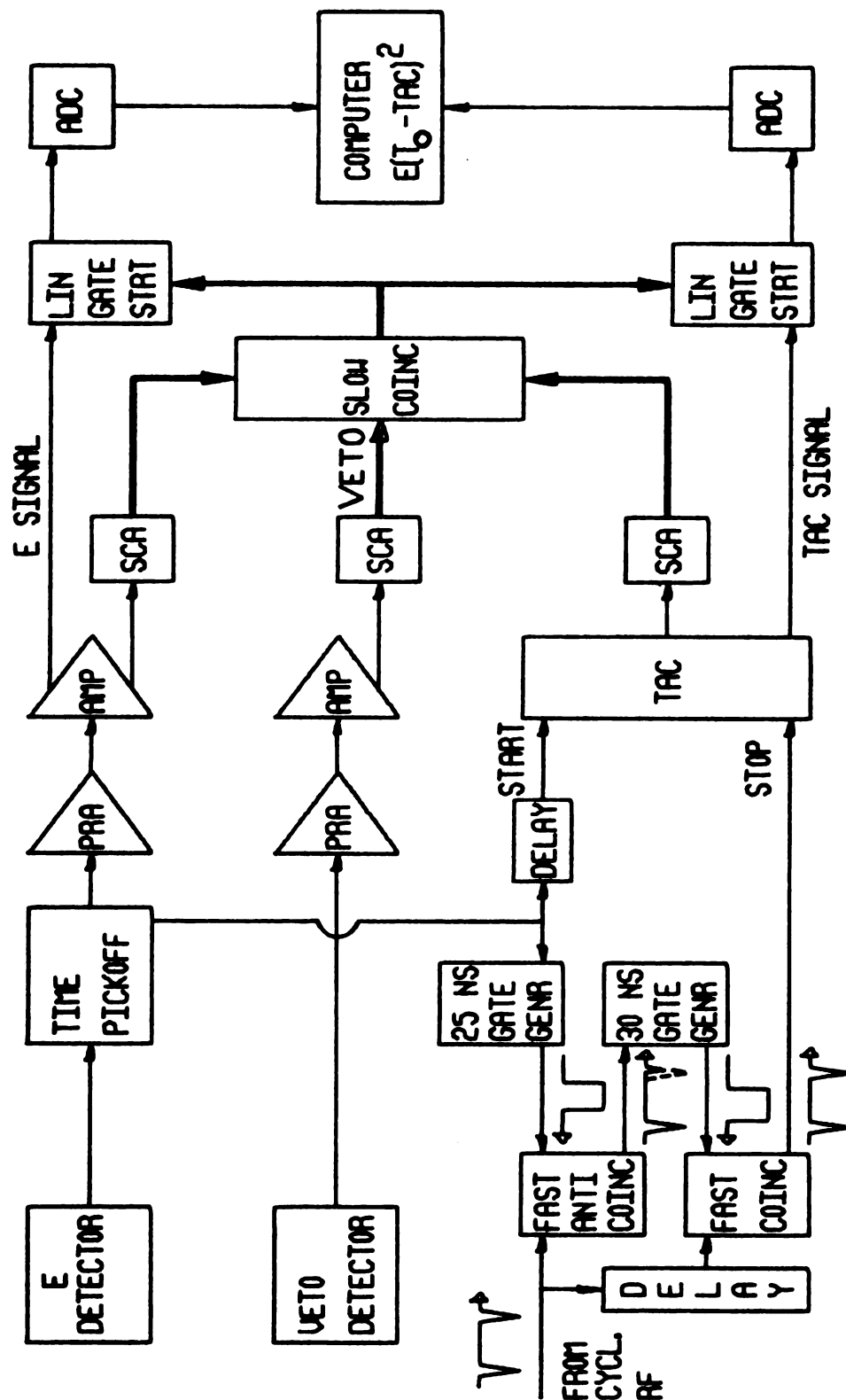


Figure 7. Electronics Block Diagram for Charged Particle Time-of-Flight.

Table 2. Electronics Equipment.

Unit	Model Number and Manufacturer
(ADC) Analog to digital converter	629 Northern Scientific
AMP amplifier	440 ORTEC
COMPUTER	SIGMA 7 XDS
Detector, E and Veto	Si surface barrier ORTEC
Fast anticoincidence one module	C102B/N EG+G
Fast coincidence	
Gate generator, 25 and 30 NS, one module	121LRS
TAC time to amplitude converter	437 ORTEC
Time pickoff	260 ORTEC
Time pickoff control	403A ORTEC
SCA Single-channel analyzer	420A ORTEC
Slow coincidence	418 ORTEC
Linear gate stretcher	442 ORTEC
PRA preamplifier	109A ORTEC

do this in a fashion which also maintains the dynamic range of particle flight times, logic has to be done on the start and stop signals. The start signal triggers a discriminator which is set to give a 25 nsec long positive going pulse. This pulse and the RF pulse are presented to a fast coincidence operated in anticoincidence mode. Only RF pulses which come later than 25 nsec after the start pulse yield an output signal. Figure 8 represents three situations of the start and stop pulse relationship. Time increases from left to right. In each set of pulses the first line represents stop pulses, the second line is the 25 nsec gate pulse generated by the start pulse in line three. Line four schematically represents the height of the TAC pulse by the length of the rectangular pulse shown. The first set shows the stop pulse arriving later than 25 nsec after the start pulse; the second set is an example of the first stop pulse coming within 25 nsec of the start pulse and the third set illustrates the nonlinear effect for stop pulses arriving ≈ 25 nsec after the start pulse. To avoid the nonlinear effects for signals which are close to the edge of the 25 nsec pulse and hence are partially attenuated (see Figures 7,8), the second channel of the LRS model 121 is used to provide a negative going 30 nsec pulse for each accepted RF pulse. This negative pulse and the original RF pulse appropriately delayed are fed into the second channel of the fast coincidence module. A uniform RF stop pulse with the correct time relation to the start

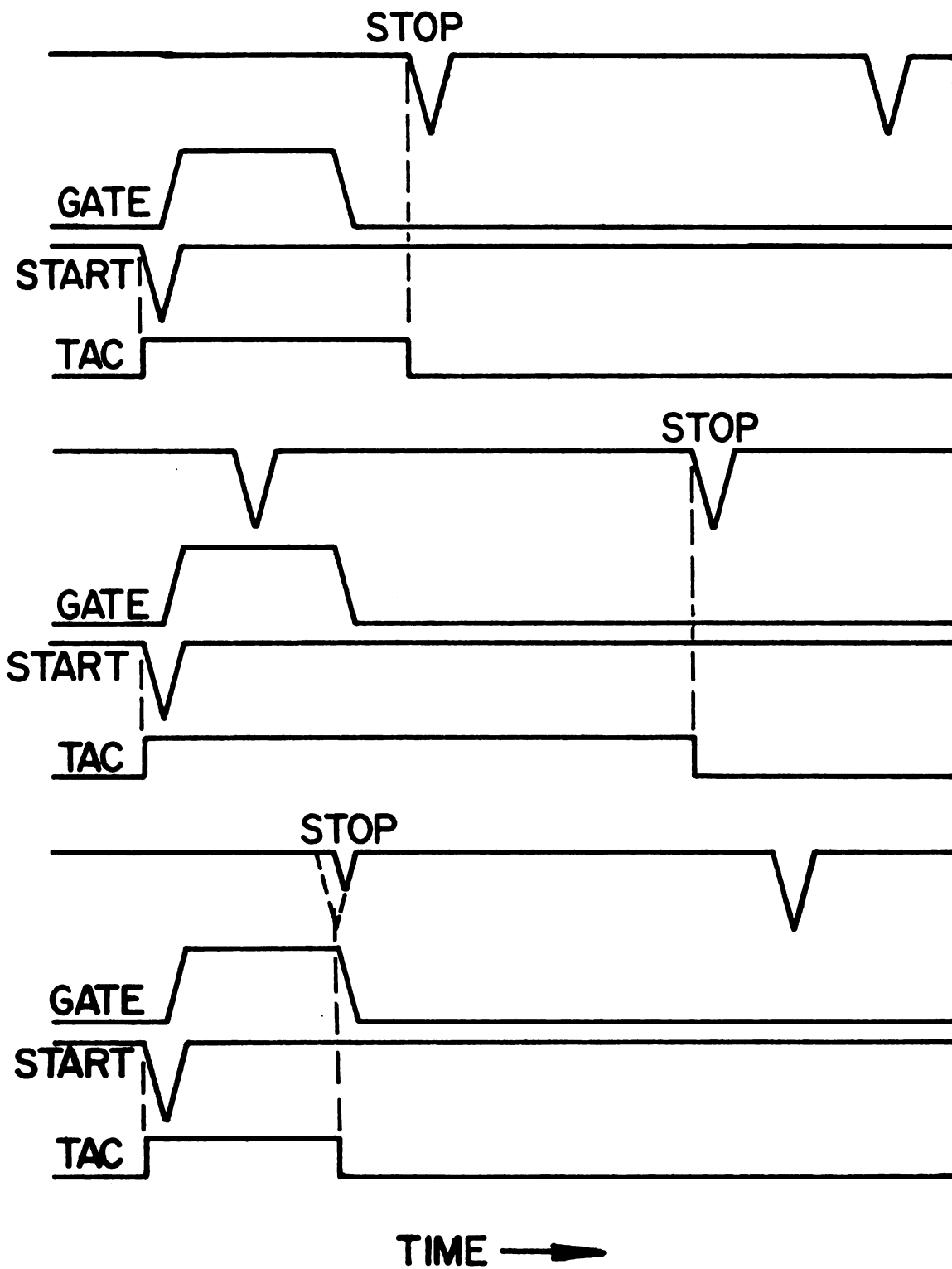


Figure 8. Start, Stop and TAC Pulses.

pulse is obtained by this means. Of course the start pulse presented to the TAC has to be delayed by the time needed to perform these logic operations. With the noted choice of start and stop pulses, fast particles, hence short flight times, are associated with large TAC pulses, while slow particles are associated with small TAC pulses. A pulser simulating events should produce a flat, continuous random time spectrum. The smallest TAC pulse should represent 25 nsec delay between start and stop, while the largest TAC pulse should represent $(25 \text{ nsec} + 1\text{-RF-period})$ delay.

The energy pulse from the preamp is fed into an amplifier. A single-channel analyzer in the integral mode provides a logic pulse for each energy pulse above a set level. Similarly the TAC pulses are fed into a single channel analyzer for logic pulses. To be able to discriminate out particles passing through the front detector, a detector placed behind it provides veto pulses. The single channel analyzer pulses from the energy signal and TAC signal are fed into the coincidence input of a slow coincidence circuit while the veto pulses are fed into the anticoincidence input. Linear gate-stretchers for energy and TAC linear signals are gated by the coincidence logic output. These are presented to 8192 channel ADC's. The ADC's are then read by the XDS Sigma 7 Computer.

2.9 The 17 MeV Measurement

The lowest proton energy available with good timing characteristics and sufficient beam intensity is presently

near 22 MeV. The cross-sections for masses 7, 10, 11 from proton spallation of ^{14}N are still large at this energy.

It was thus very desirable to perform a cross-section measurement at a lower energy, lowering the beam energy by introducing a degrader. In Appendix E are calculations to choose degrader material and thickness. Aluminum is better than heavy elements such as lead in terms of energy spread caused by degrading the beam by a fixed energy differential.

Aluminum is also advantageous since when irradiated by protons the radioactive products have comparatively short half-lives and handling equipment after irradiation is less of a problem. The beam emerging from the degrader also has an increased angular spread. It is therefore important to position the degrader as close to the gas cell as possible. Since the resolution is still quite marginal for masses 10 and 11, it was desirable to have the display for the non-degraded beam as a guide. Therefore a mechanism for inserting and removing the degrader was devised. A solenoid was designed to lift the degrader in and out of the beam path at 0.25" from the Kapton gas cell window. The mechanism could be actuated in less than a second. This made it possible to compare instantaneous beam intensity ratios with the degrader in and out of the beam. Due to the angular spread not all of the degraded beam was collected in the Faraday cup. Spot checks were made throughout the experiment to determine the ratio. The total charge collected was scaled by the average of these rather constant ratios.

The beam degrader chosen was 0.085" thick 6061 aluminum alloy. For the proton beam energy of 21.65 MeV the degraded beam energy is calculated in Appendix E to be 16.8 MeV. Experimentally the degraded beam energy was determined to be 17.2 MeV \pm 0.2 MeV from the cesium iodide monitor spectra for degraded and direct beam.

3. DATA ACQUISITION

3.1 On Line Setting Up Procedure for Data Taking

3.1.1 Introduction

When the proton beam is first brought into the scattering chamber, the detector-gas cell assembly is removed. The beam is focused on a plastic scintillator at the center of the scattering chamber. The beam spot on the scintillator is viewed by remote TV. Once a satisfactory spot, appropriately centered on the scintillator, is obtained, the gas-cell-detector assembly is positioned in the scattering chamber. Manometer, gas cell and scattering chamber are evacuated. The gas cell is then filled with the gas target of interest to the pressure desired. The detector is replaced and the detection angle is set to 15° with respect to the beam which is again brought into the scattering chamber.

3.1.2 Software

Data taking is done under the all purpose code TOOTSIE, written by Douglas L. Bayer (BA 71). Data is displayed at run time on a Tektronix 611 storage scope. Data and display are manipulated and interacted with by both teletype and switch commands.

The EDE mode of TOOTSIE is used for choosing the correct delay for RF stop pulses. In this mode TOOTSIE plots two variables, x-axis=energy pulse, y-axis=TAC pulse as shown in Figure 9.

Starting with the first display, where the timing pulse of the fastest particle arrives sometime between RF stop

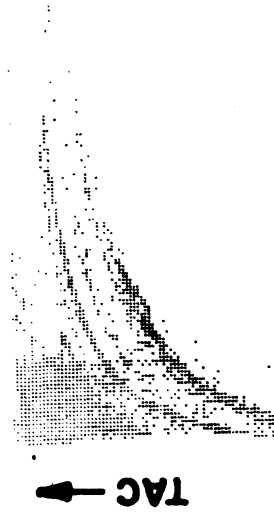
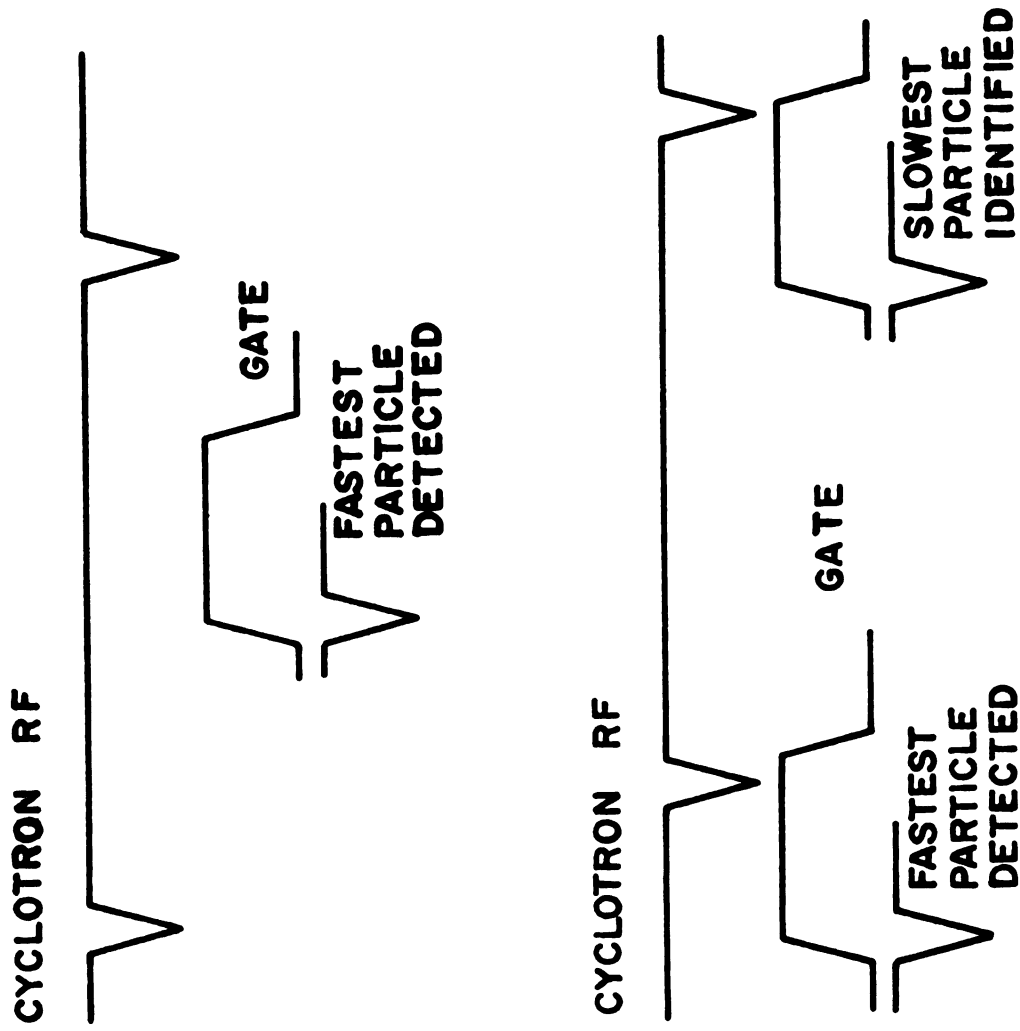
INPROPER TIMING**ENERGY →****PROPER TIMING****ENERGY →**

Figure 9. Stop Pulse Timing Adjustment.

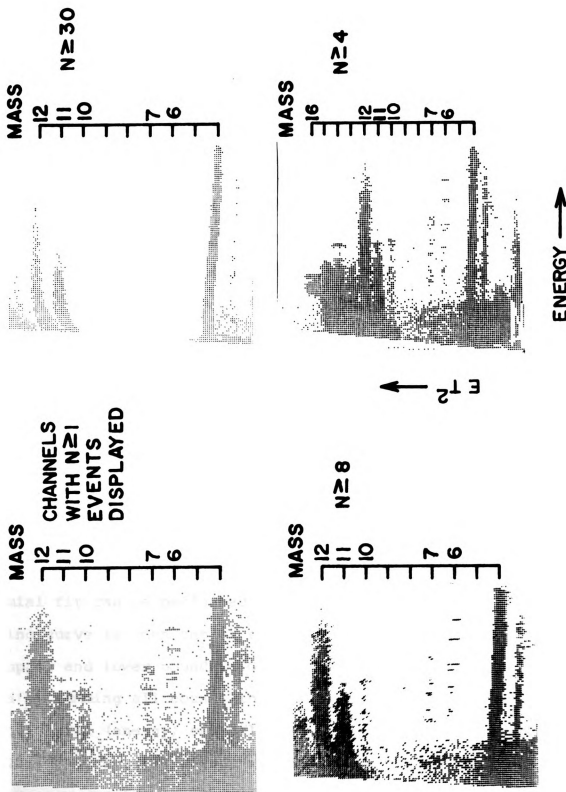


Figure 10. Mass Band Displays.

pulses, delay is added to (or subtracted from) the RF stop pulses until the second display, with the timing relation indicated, is obtained. Optimum delay is such that the fastest particle of interest has the longest TAC pulse (25 nsec+1 RF period). The slowest particle that can then be identified will come one RF period later and will have a TAC pulse equivalent to 25 nsec. Once the RF delay has been determined, the E*T**2 option of TOOTSIE is entered. In this mode the quantity $[A+E*(TAC-TZERO)**2/NORM]$ is plotted against E on a two-dimensional analyzer. E is the energy signal and TAC is the time signal. The parameters A, TZERO, and NORM are selected at run time to display data in the most convenient form (see Figure 10).

3.2 Data Taking

Once the parameters are satisfactory, data is accumulated. Energy spectra of the various masses can be derived from the two-dimensional display. An option in TOOTSIE makes it possible to define upper and lower bounds of a mass band. This is done by choosing points with a cross which is moved from scope switches. Up to a ninth degree polynomial fit can be performed on these points. The resulting curve is then one of the mass band boundaries. Given upper and lower bounds, TOOTSIE generates energy spectra by summing all counts in the band identified by the same horizontal (energy) channel number. Since data is taken on a 128x128 array, the energy spectra are 128 channels long. Sample energy spectra are shown in Figure 11. The complete

two-dimensional array as well as the energy spectra derived from it were punched on cards. The data, as read from the ADC's can also be stored on tape. The tape can later be read by TOOTSIE and the data can be reanalyzed. It is thus possible to use different parameters to display portions of the data for easier analysis. Figure 10 shows four oscilloscope displays for the data from ^{16}O for 37.9 MeV protons with the detector at 15° to the beam. One display shows all data up to mass 16; by using a different set of values for the parameters NORM and A, and by displaying only those channels which have N or more events, one obtains the other three displays (N=1, N=8, N=30). The valley between mass 11 and 12 can thus be seen on the (N=30) oscilloscope display. The nonlinearity (mass defect) of the mass bands toward low particle energy is due to incomplete charge collection by the detector.

Background events, presumably neutron induced reactions in the silicon detector, contaminate the spectrum at low particle energy as is evident in Figure 10. This data represents the most severe case. For lower energy proton beams the background is considerably less. Since ^{14}N spallation cross-sections are considerably larger, background is less of a problem even at high proton beam energy for that target. For the 41.9 and 37.9 MeV data, background runs were taken with no gas in the cell. Cross-section calculations in Table 8 and angular distributions for these runs are labeled "Vac". The cross-sections summarized in Table 9 are corrected for this contribution.

3.3 Dead Time Correction

Dead time of the analog to digital converters (ADC) is monitored using the option "channel zero" in the program TOOTSIE (BA 71). A logic pulse presented to channel 0 is counted only if the ADC's are free to accept an event. Thus the ratio of the number of counts in channel zero to the number of pulses presented is the fractional lifetime of the ADC's. The source of pulses for channel zero has to be chosen carefully. For example if the beam intensity fluctuates, then a random or fixed frequency pulser will indicate less deadtime than is actually the case. Suppose, for example, that the beam is off for 9 sec and on for 1 sec periodically; then even if the ADC's are completely dead during the 1 sec, the channel zero count will indicate only 10% deadtime while actually the deadtime is 100%. This shows the channel zero pulses should come from a source which is directly correlated with scattered particle intensity. The proton elastic peak monitor was used for this purpose.

3.4 Mass Band Resolution

For the correct choice of TZERO the quantity $(TAC - TZERO)$ is proportional to the flight time t of the particle. Beam bursts have a finite duration; flight path length varies for different particles; and the energy resolution of the detector is not perfect; hence what is ideally a series of sharp lines representing the energy spectra of different masses, becomes a set of bands. As shown in Appendix G the width of a band is governed by the equation:

$$\text{width of band} = \Delta(Et^2) = Et^2 [(\Delta E/E)^2 + 4((\Delta x/x)^2 + (\Delta t/t)^2)]^{1/2}$$

E = energy,

X = flight distance,

t = flight time,

ΔE = energy resolution,

ΔX = uncertainty in the flight distance

Δt = width of the beam pulse.

Suppose the quantity Et^2 is given in mass units. To separate one mass band from the next, $\Delta(Et^2)$ should be less than one mass unit. From the equation for $\Delta(Et^2)$ it can be seen that the higher the mass, the more difficult it is to resolve it.

To resolve mass m the fraction $\Delta(Et^2)/Et^2$ must be less than $1/m$. This represents 17% resolution for mass 6 and 9% resolution for mass 11. Table 3 summarizes individual contributions to the mass resolution as discussed in Appendix G. The observed band width can be accounted for by these contributions. Table 4 gives a specific example. It is fortunate that for low energy particles where energy resolution starts to become significant, the beam time-resolution is less limiting than for higher energy particles.

Table 3. Individual Contributions to $\Delta(Et^2)$ in Terms of Percentage of Et^2 .

<u>Particle Energy ΔE</u>	
Source:	Detector resolution of 5.48 MeV α is ~ 40 kev
Max:	8% (for a 0.5 MeV particle)
Min:	0.2% (for a 20 MeV particle)
 <u>Time Resolution (Cyclotron) δt</u>	
Source:	Average width of cyclotron beam burst was 0.5 nsec (.3 to .7 nsec were measured)
Min:	1.2% (slowest particle, flight time ~ 84 nsec)
Max:	8% (fastest particle, taken to be 20 MeV mass 6, flight time ~ 12 nsec)
 <u>Time Resolution due to Δd (flight path length uncertainty)</u>	
Source:	geometry; beam width 0.040", front slit $S_2=0.040"$
Min:	0.8% (detector at 90° , holds for all particles)
Max:	5% (detector at 15° , holds for all particles)

Table 4. Band Resolution of Spallation Data from ^{14}N
by a 41.9 MeV Proton Beam.

Geometry: Detector angle 15° , beam width 0.040", front slit
 $S_2 = 0.040"$.

Particle energy considered: 5.48 MeV.

Observed mass resolution: 6 ± 1 channels FWHM for mass 11,
 4 ± 0.5 channels FWHM for mass 6.

One mass unit = 9.6 ± 0.1 channels.

Theoretical Resolution Contributions to $\Delta(Et^2)$ in % of Et^2

	<u>Mass 6</u>	<u>Mass 11</u>
Due to $\Delta E = 40$ kev	.7	.7
Due to beam burst width δt	4.4	3.3
Due to flight path length uncertainty Δd	5.0	5.0
Contributions combined in quadrature	6.7	6.0

Observed band spread percentage of Et^2 (FWHM)	7.0 ± 0.9	6.9 ± 1.1
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4. DATA REDUCTION

4.1 Energy spectra and low energy cutoff correction

Energy spectra were obtained directly from the data taking routine TOOTSIE as outlined in section 3.1.2. An alternate method was also employed based on the two dimensional array obtained in card form. A fortran program was written for converting the two dimensional data into a set of mass spectra by generating line-printer plots of the events stored in the set of channels in a line parallel to the (Et^2) axis. The mass band fitting could then be done off line. This was of advantage for two reasons; time did not have to be spent at run time to perform all band fits, and, as can be seen from Figure 9, mass separation for mass 11 is not always easily determined on the scope display. A second fortran program was written to generate 128 channel energy spectra from the two dimensional data, given the band fits determined from the printer plots.

A few energy spectra are shown in Figures 11 to 39. They are representative in the sense that the 37.9 MeV data is the lowest quality taken, while that at 25.6 MeV is among the better data sets. The energy spectra collected all have a low energy cutoff. This is usually due to the finite flight time available and the energy losses in gas and formvar window. The energy cutoff for particle detection due to detector and time pickoff sensitivity limitations is near 0.5 MeV; this represents the limiting factor for masses 6,7 for proton beam energies below 30 MeV (since then the

ENERGY SPECTRA TARGET ^{14}N $\theta_{\text{LAB}} = 15^\circ$ $E_p = 25.8$

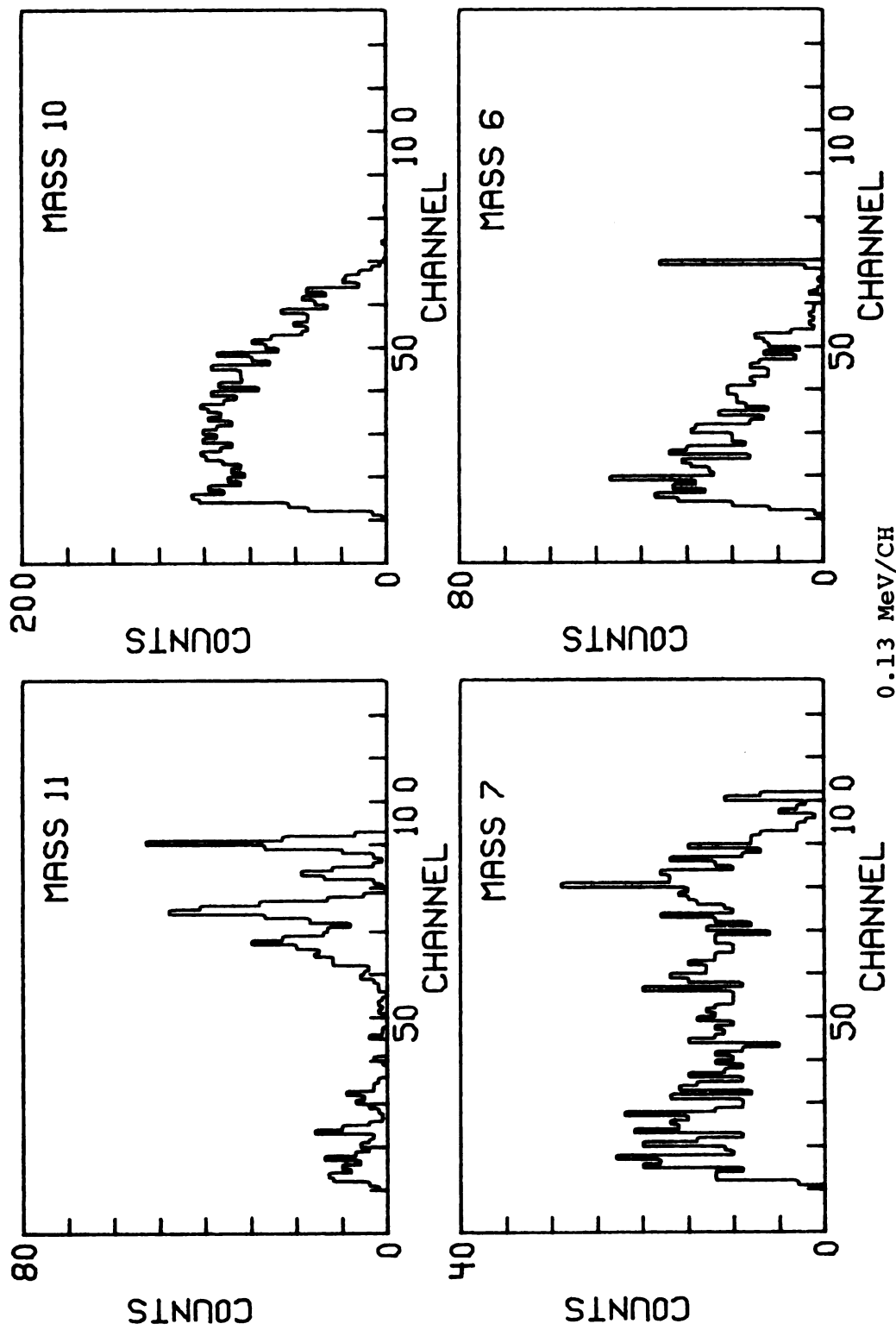


Figure 11. Selected Energy Spectra from Proton Spallation of ^{14}N and ^{16}O Targets.

Figure 11. (continued)

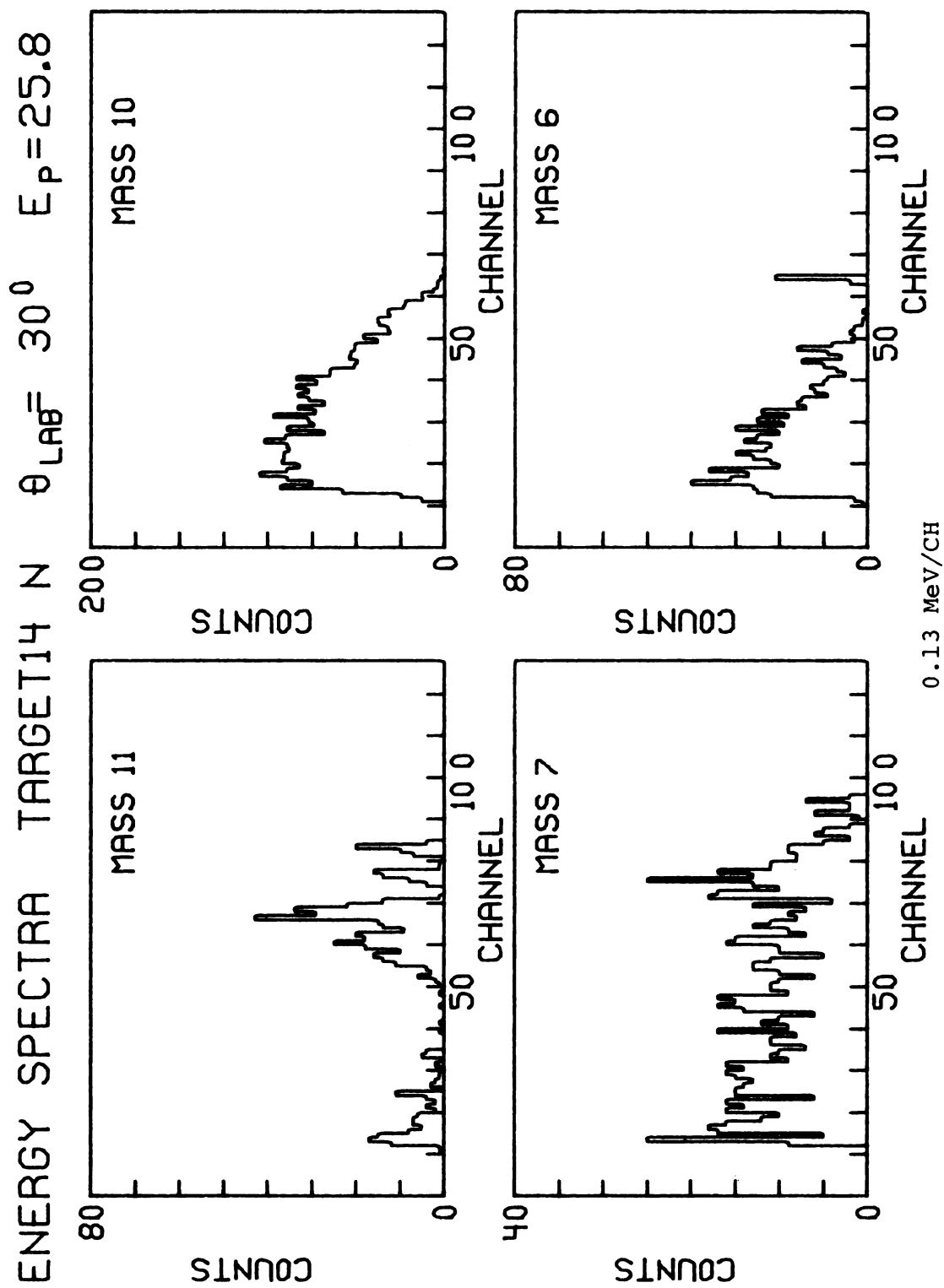


Figure 11. (continued)

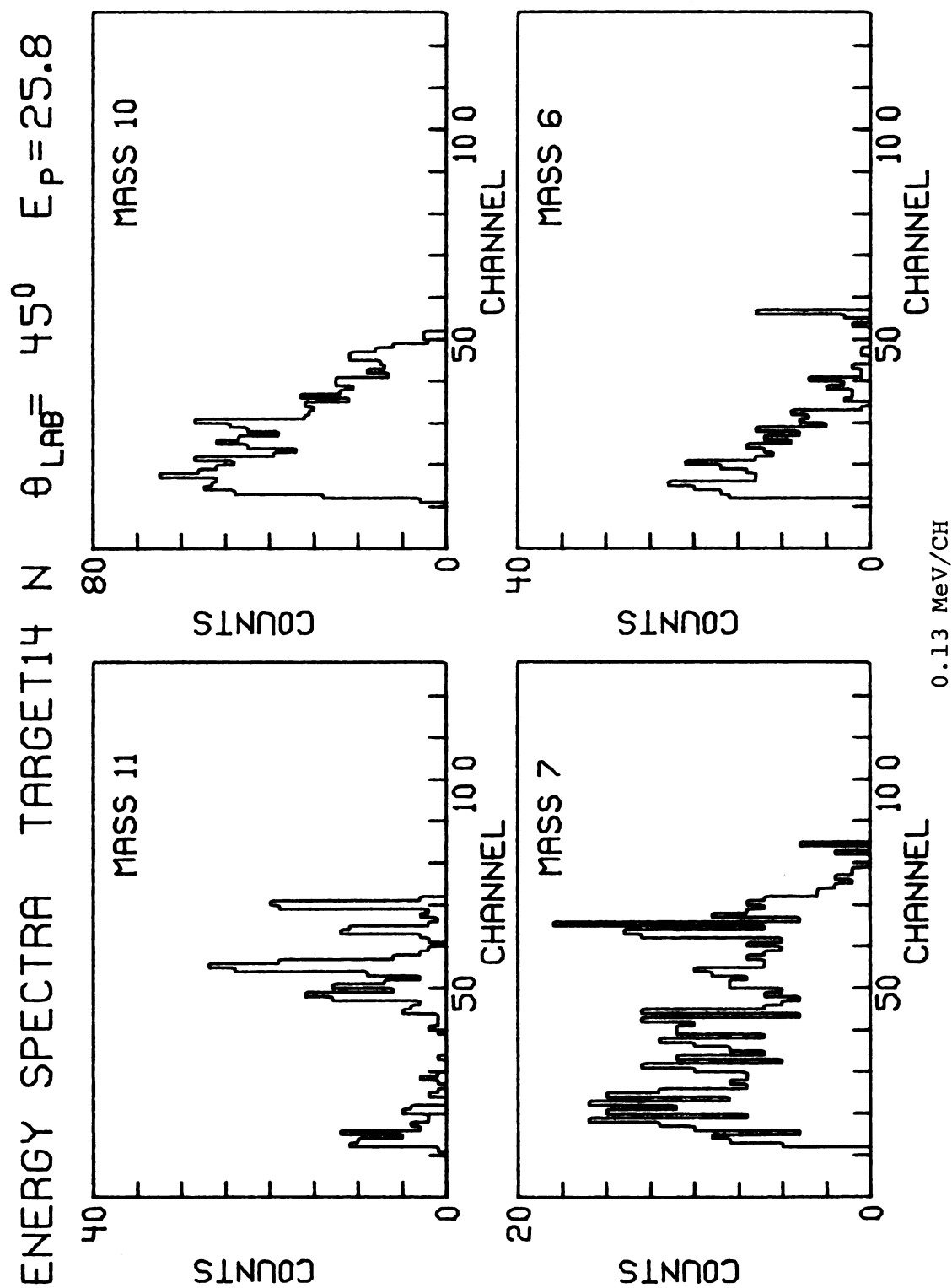


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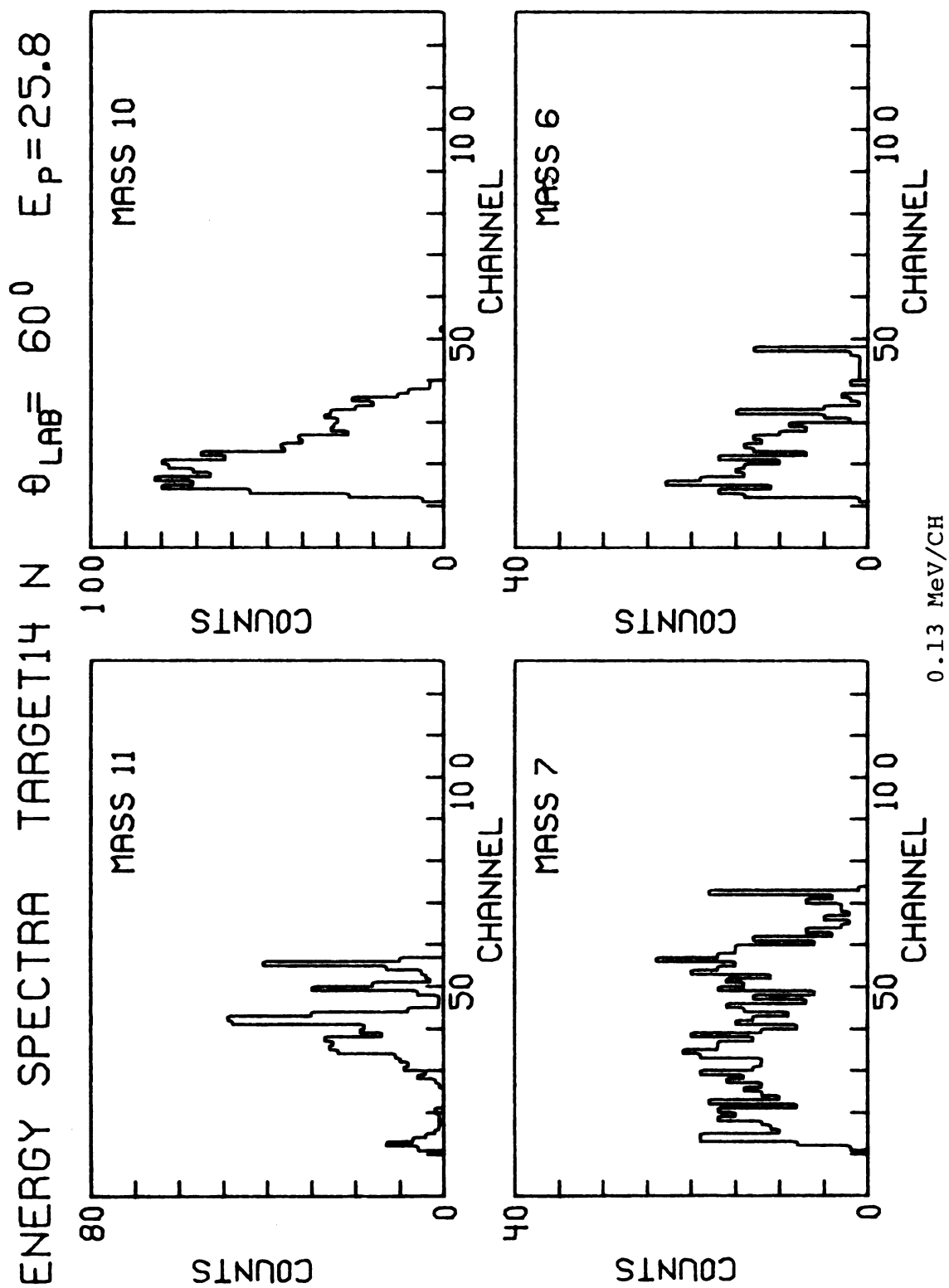


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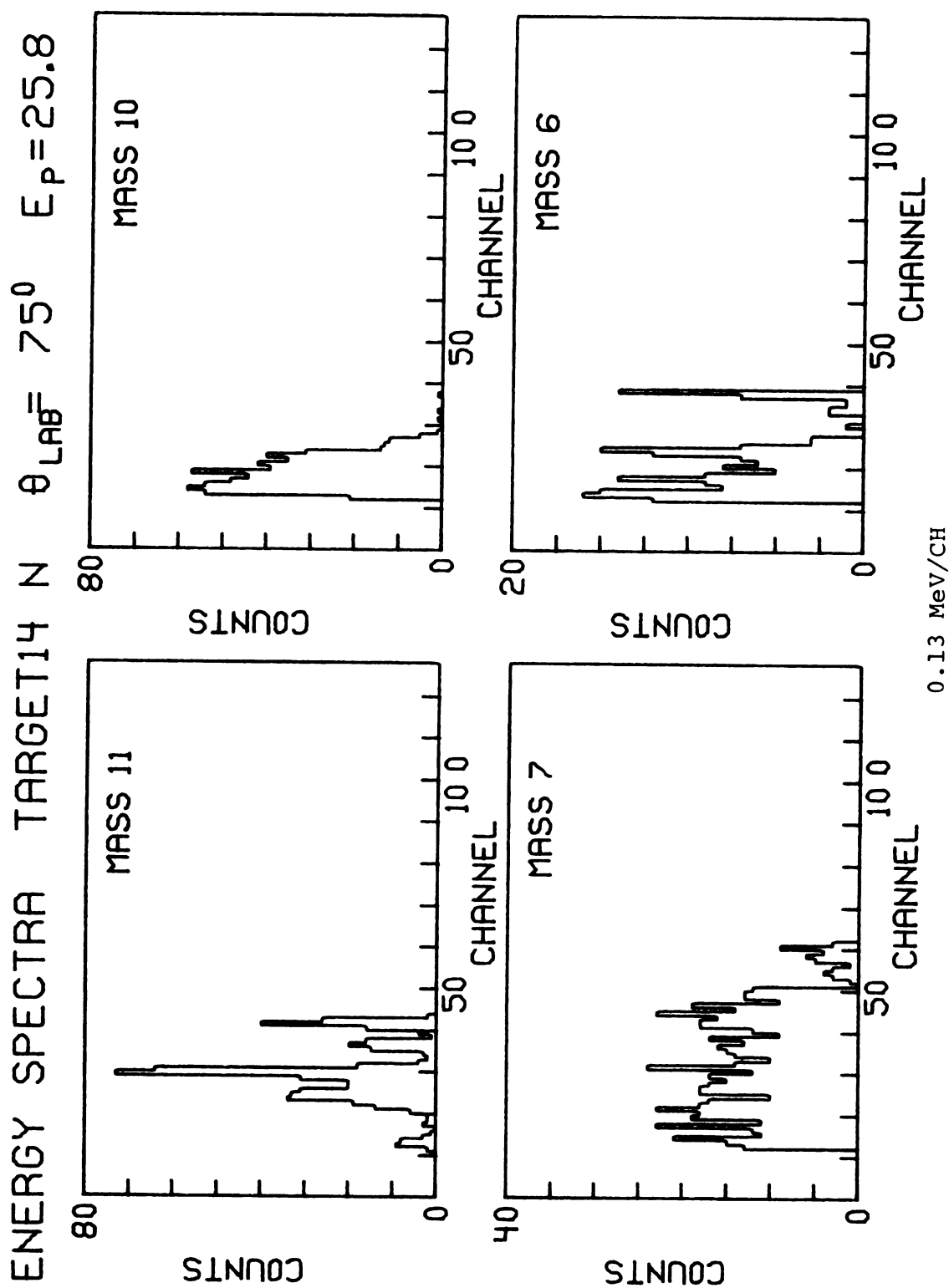


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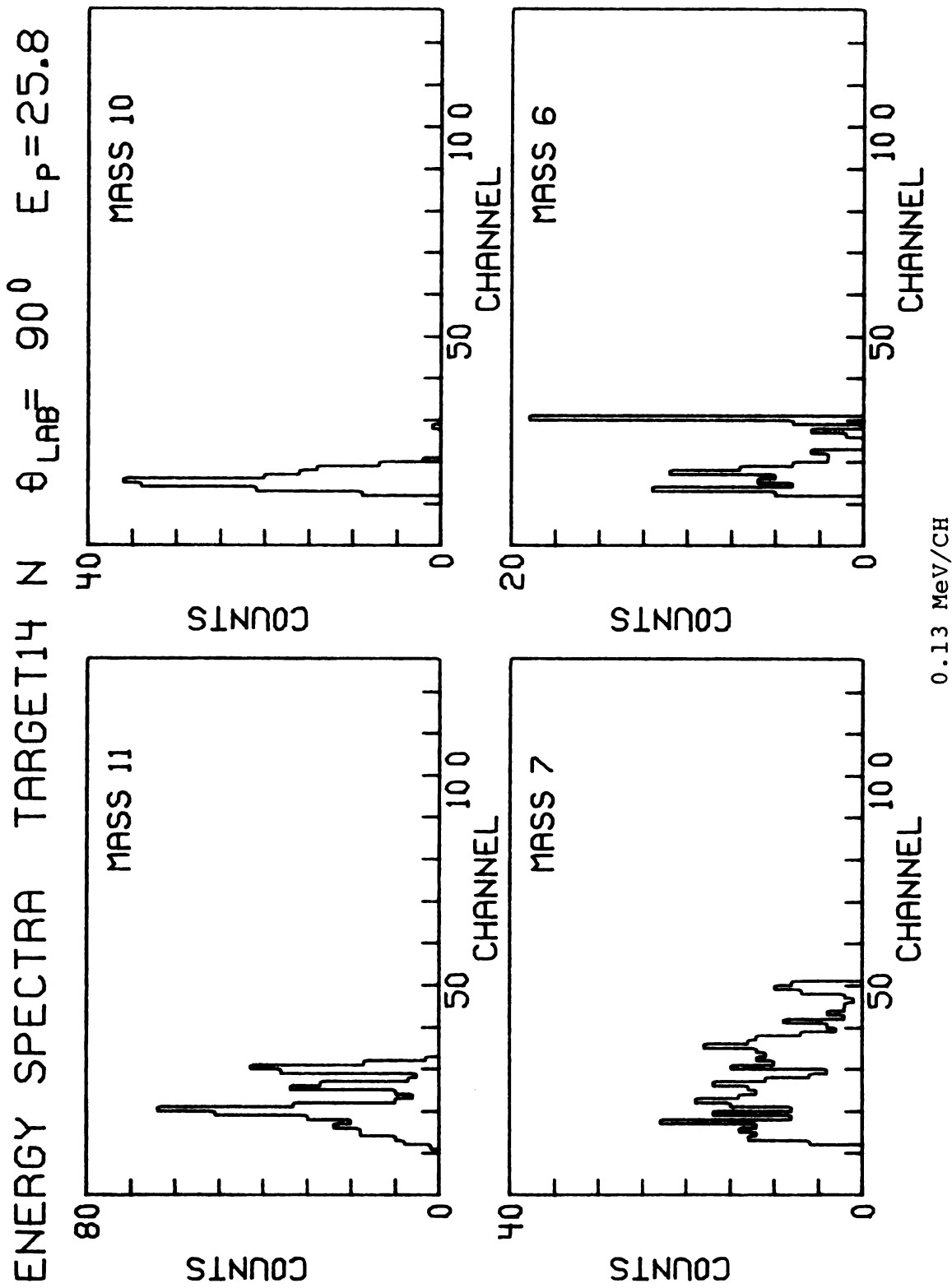


Figure 11. (continued)

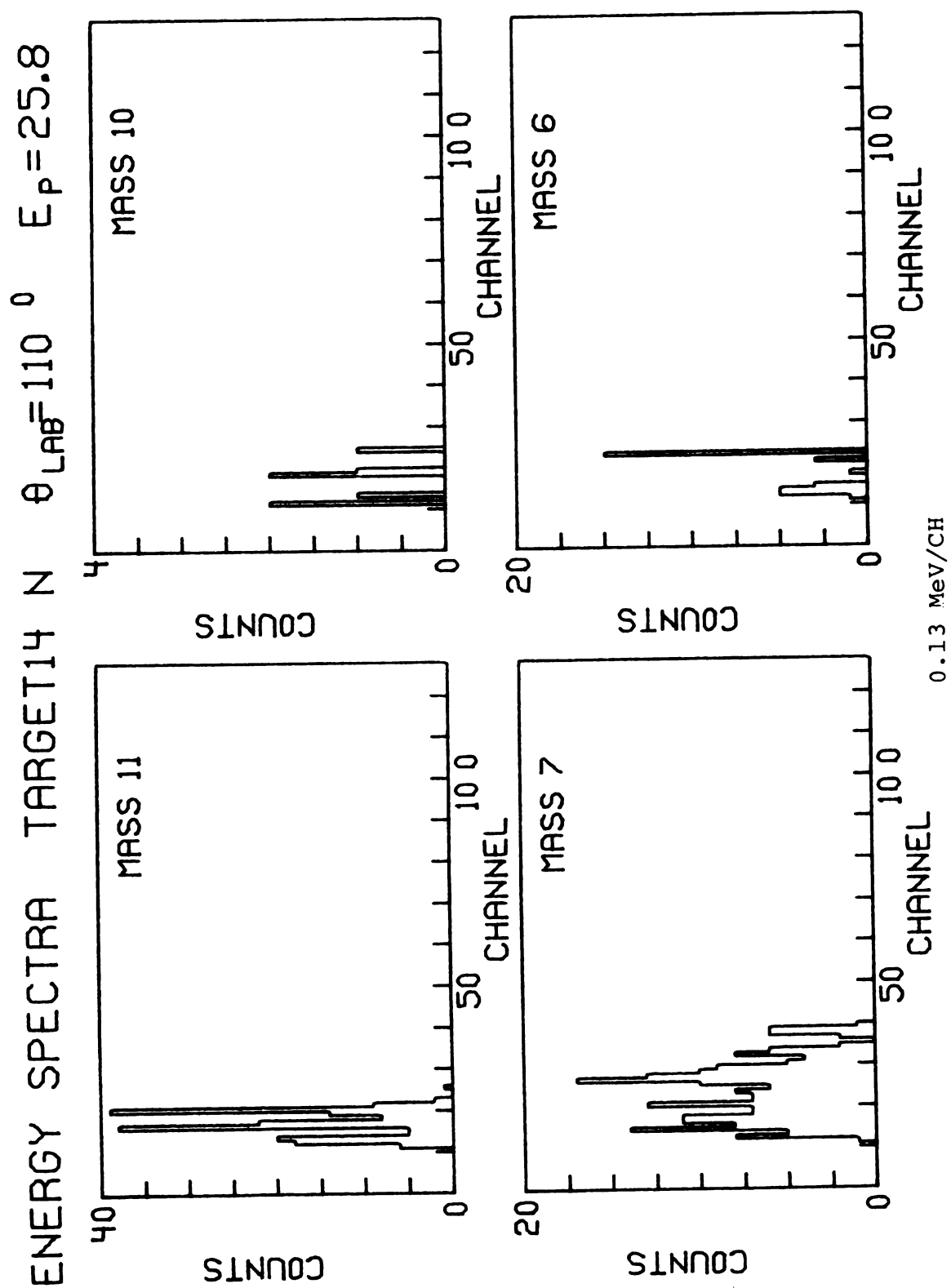


Figure 11. (continued)

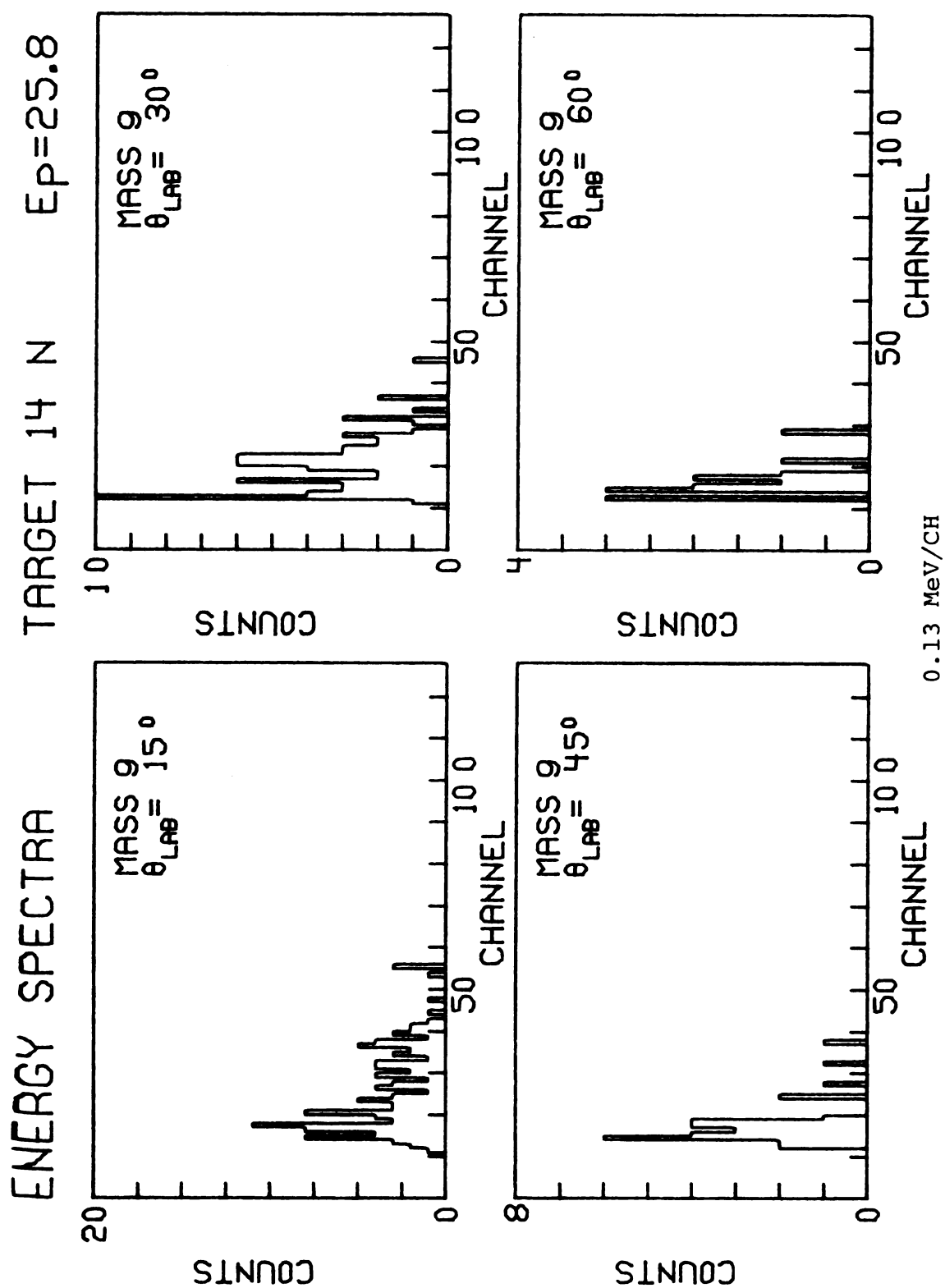


Figure 11. (continued)

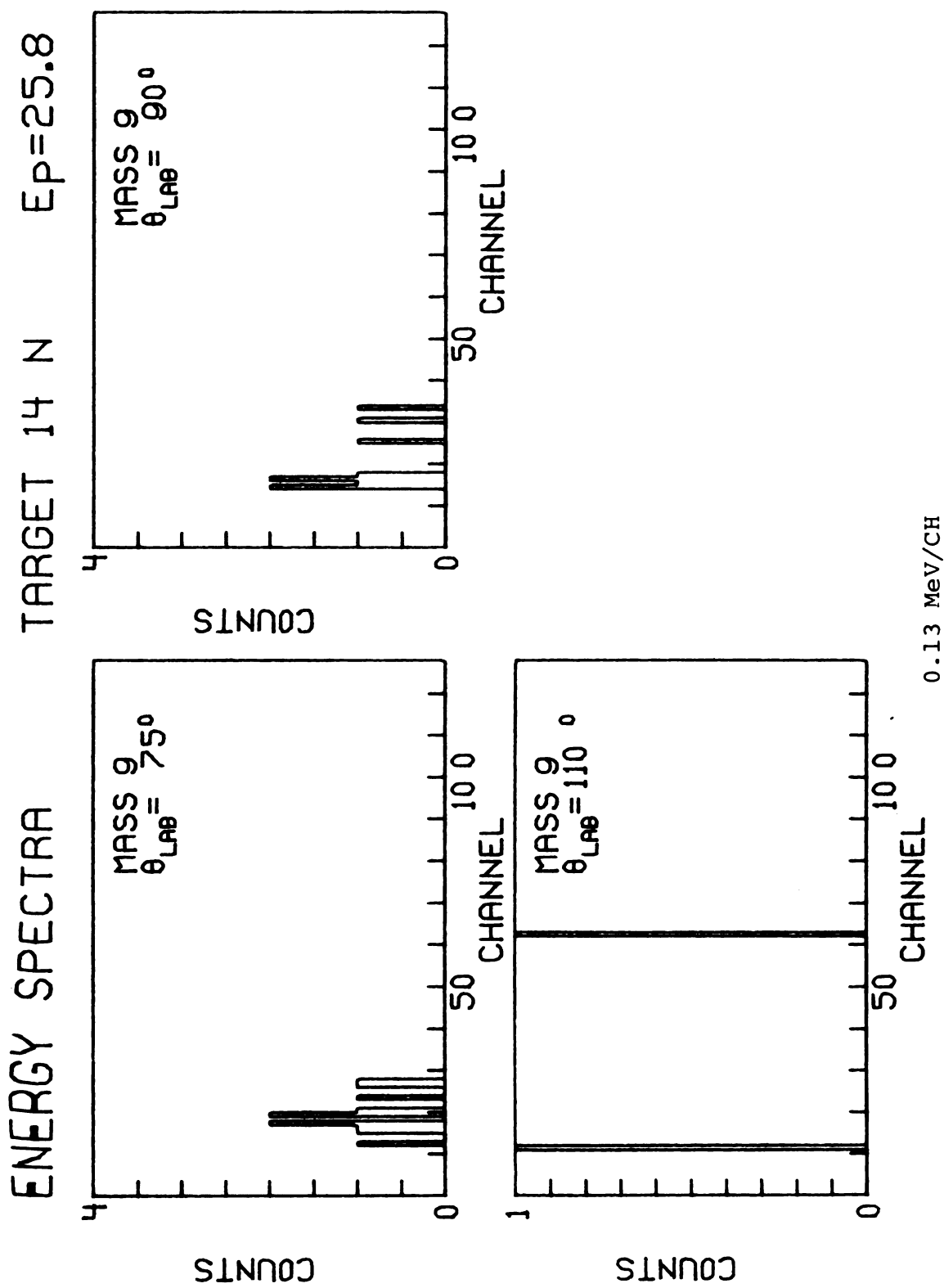


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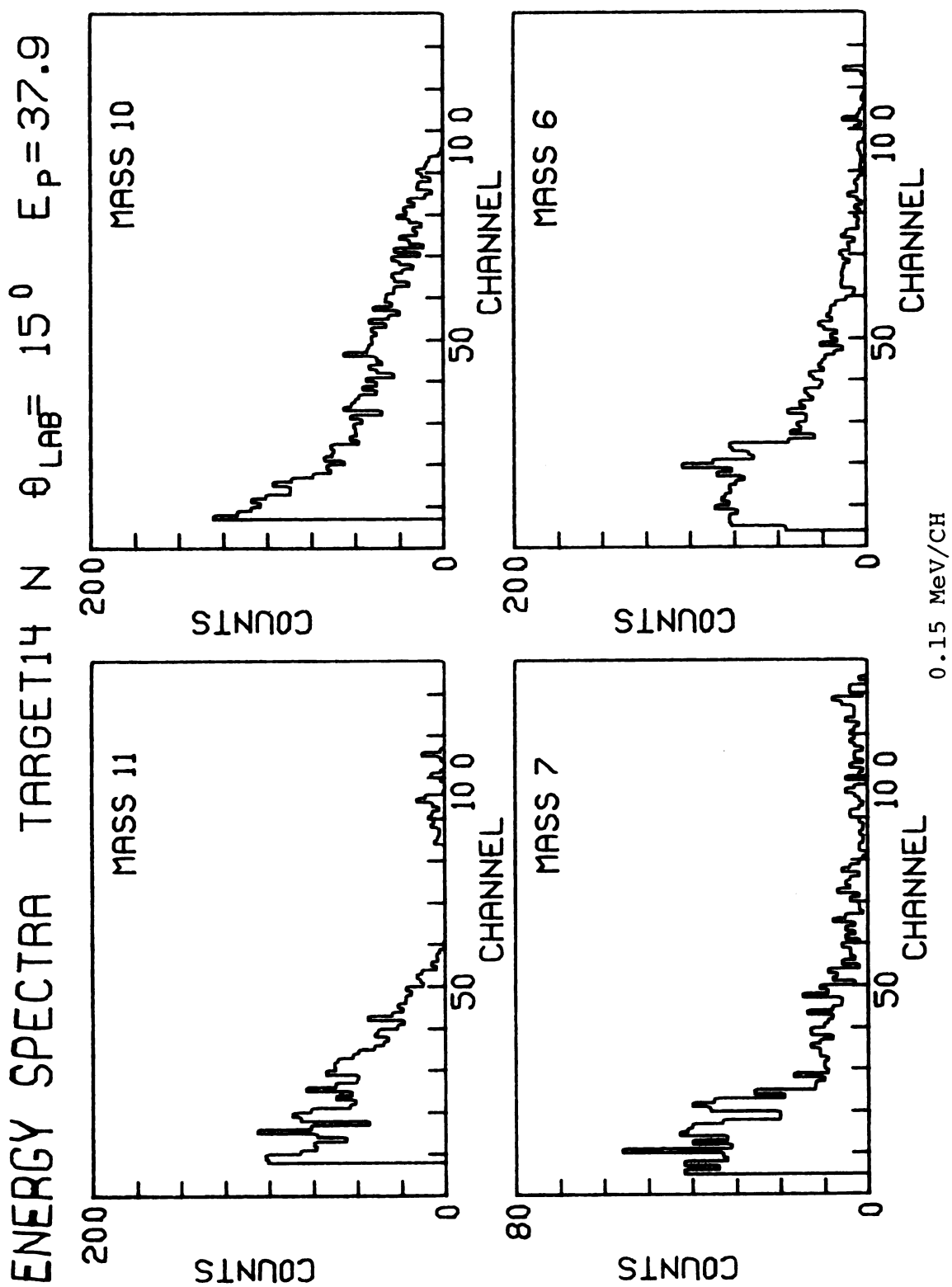


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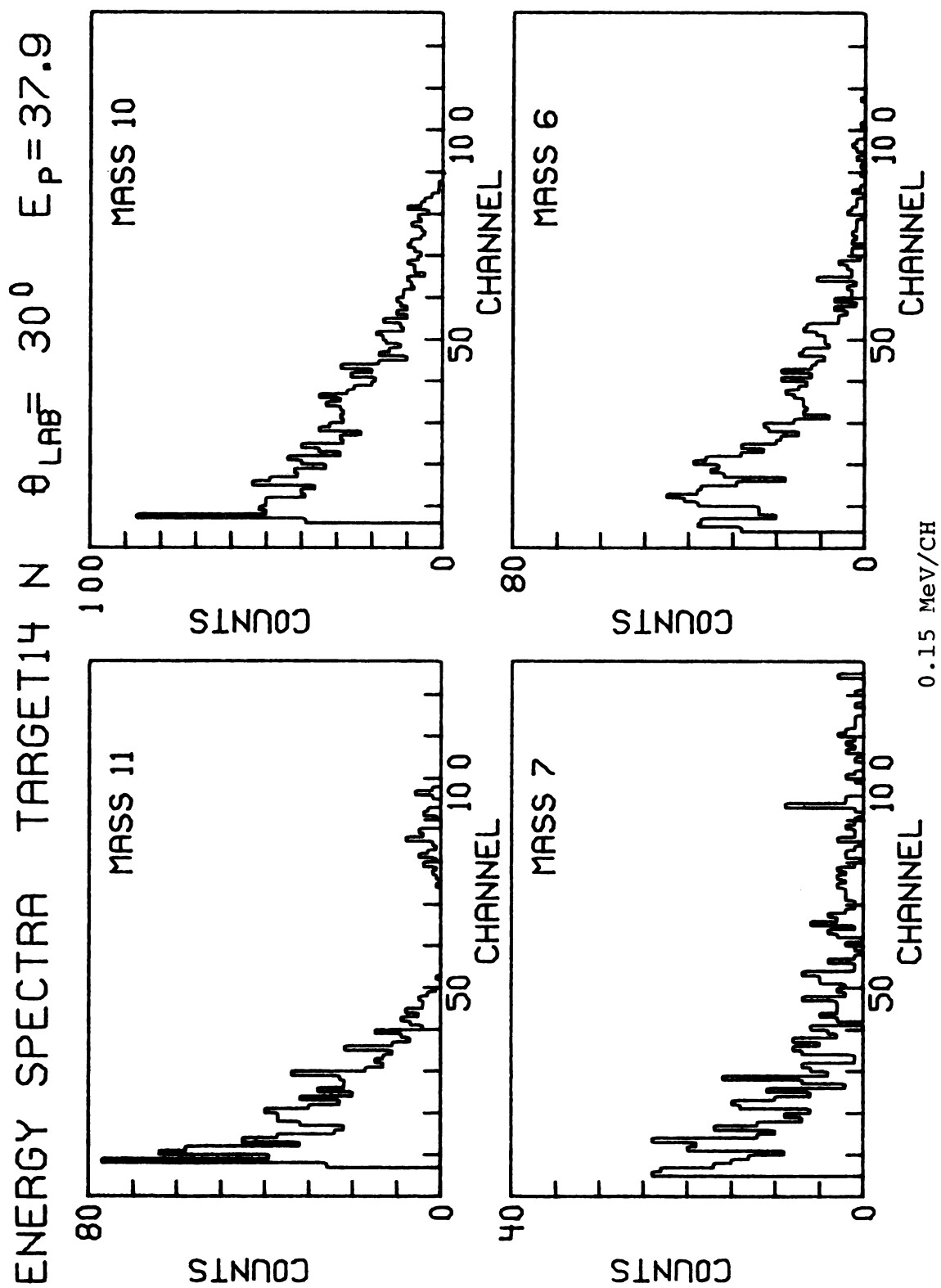


Figure 11. (Continued)

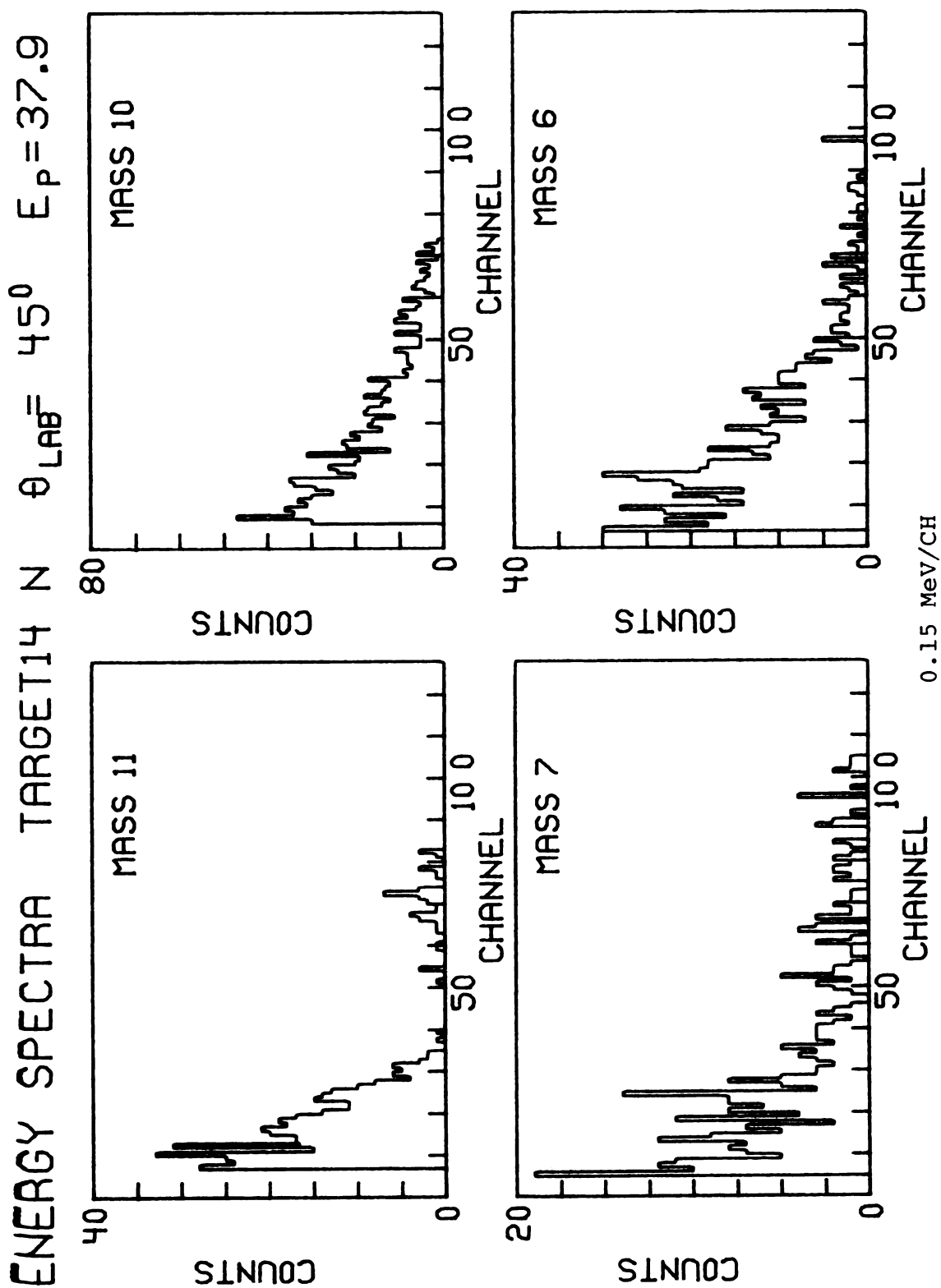


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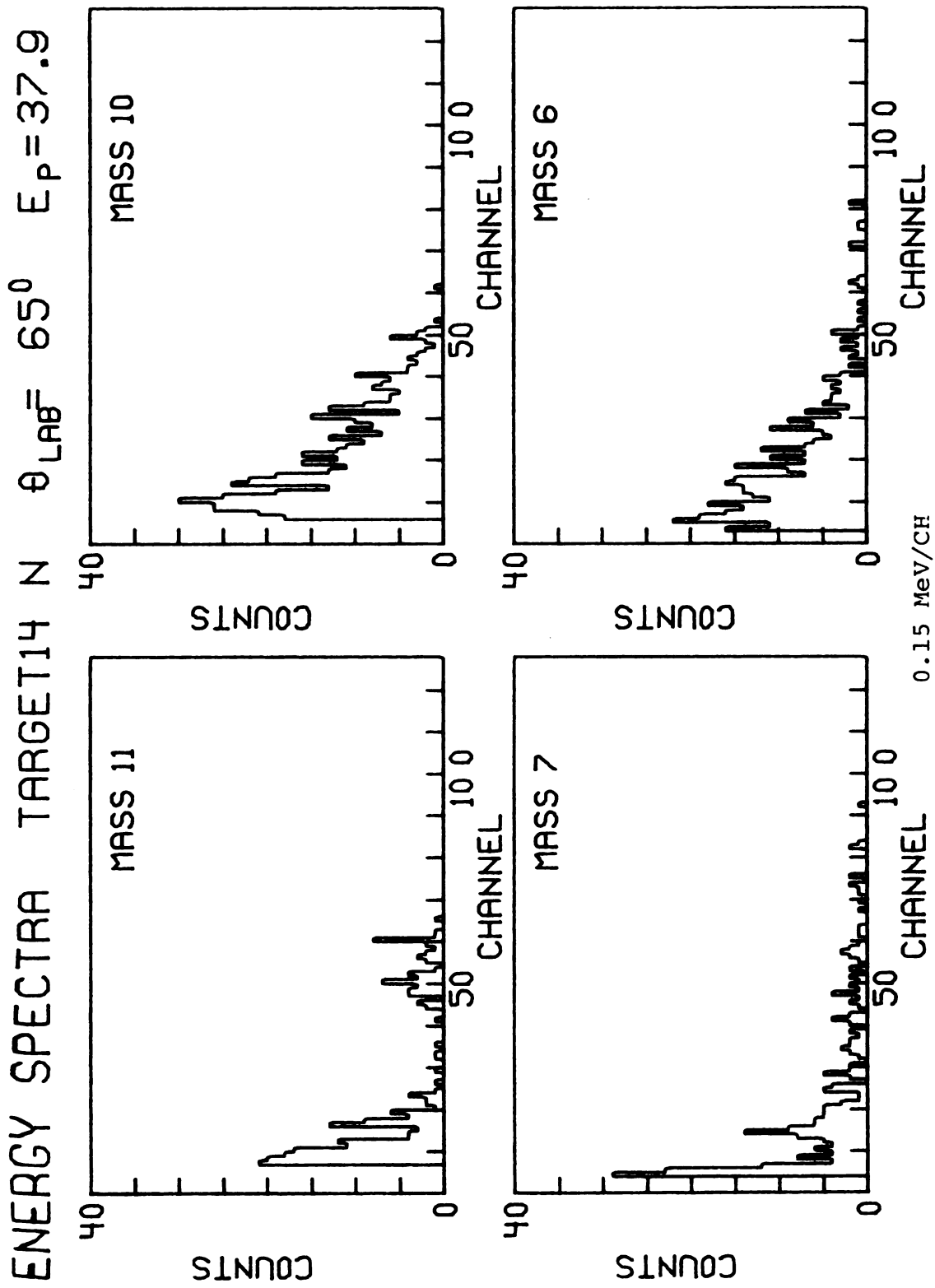


Figure 11. (continued)

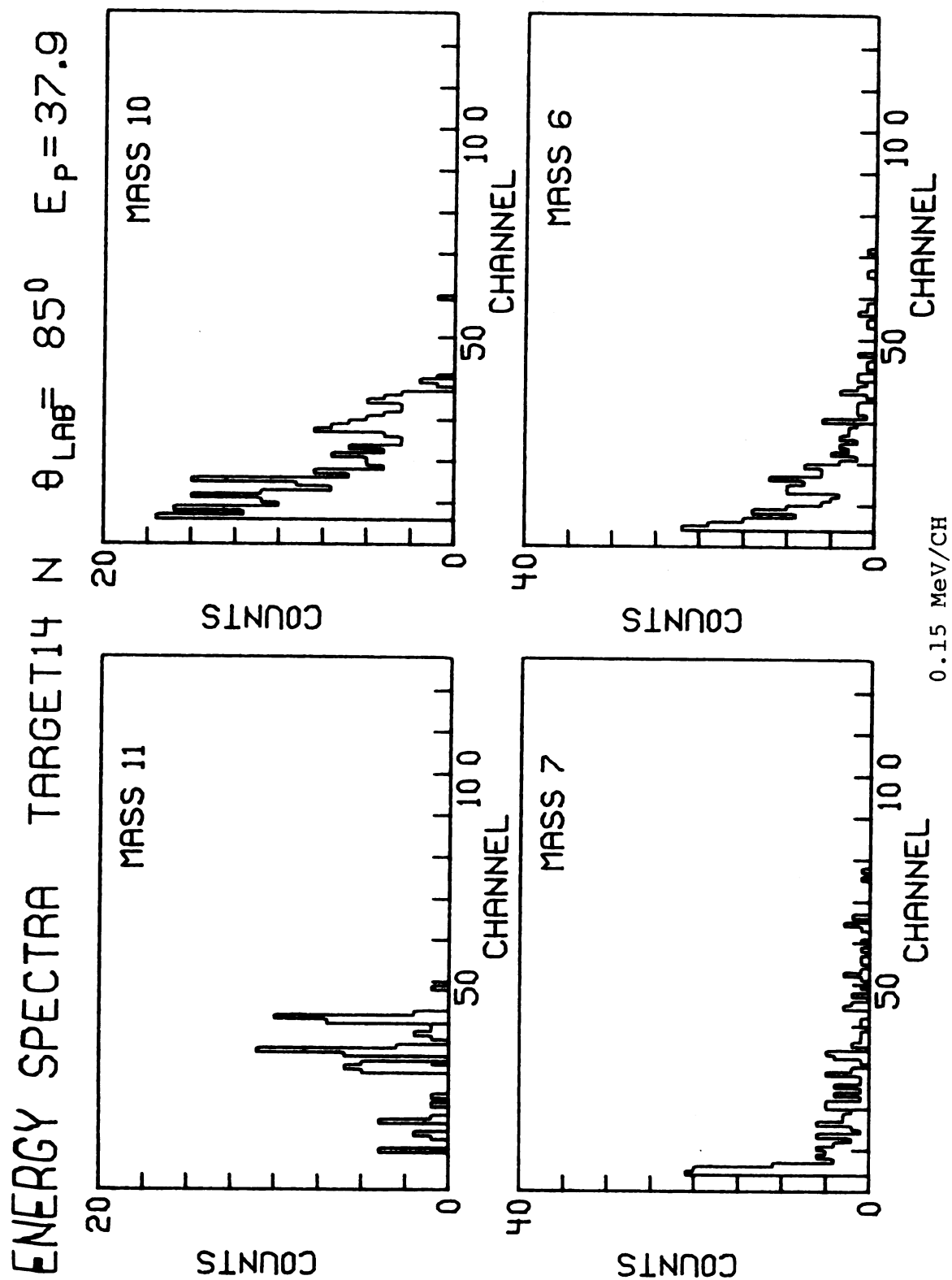


Figure 11. (continued)

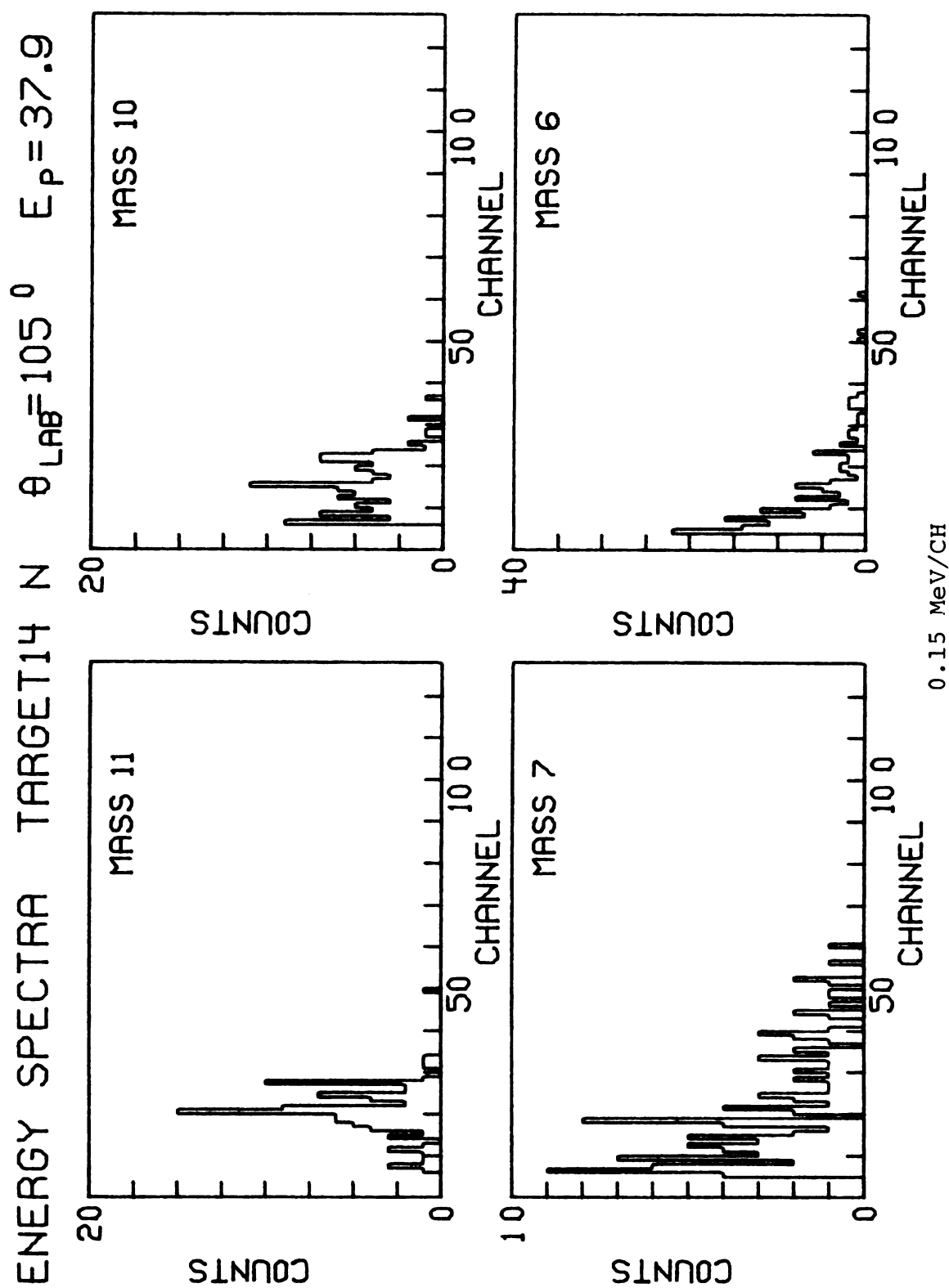


Figure 11. (continued)

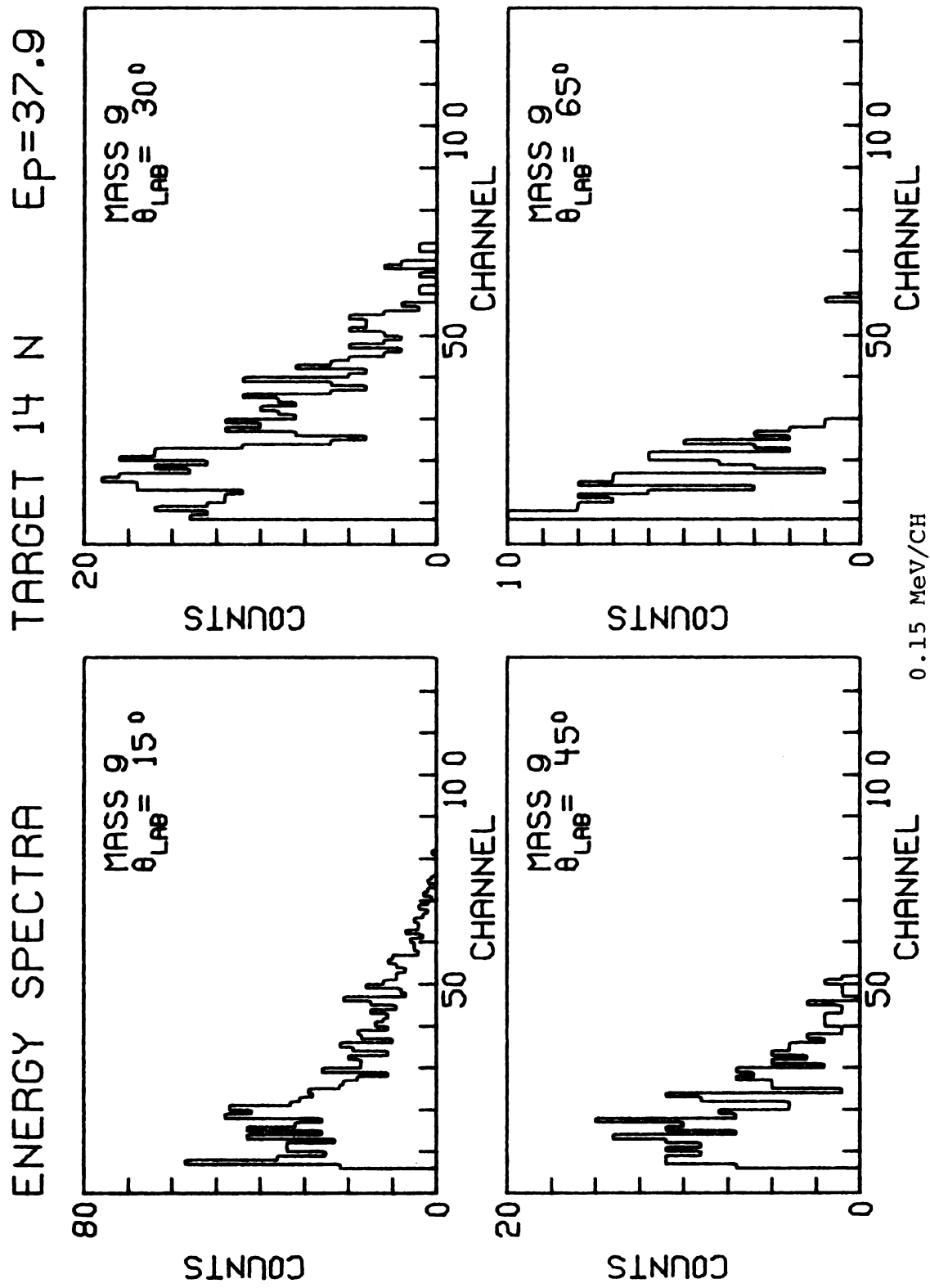


Figure 11. (continued)

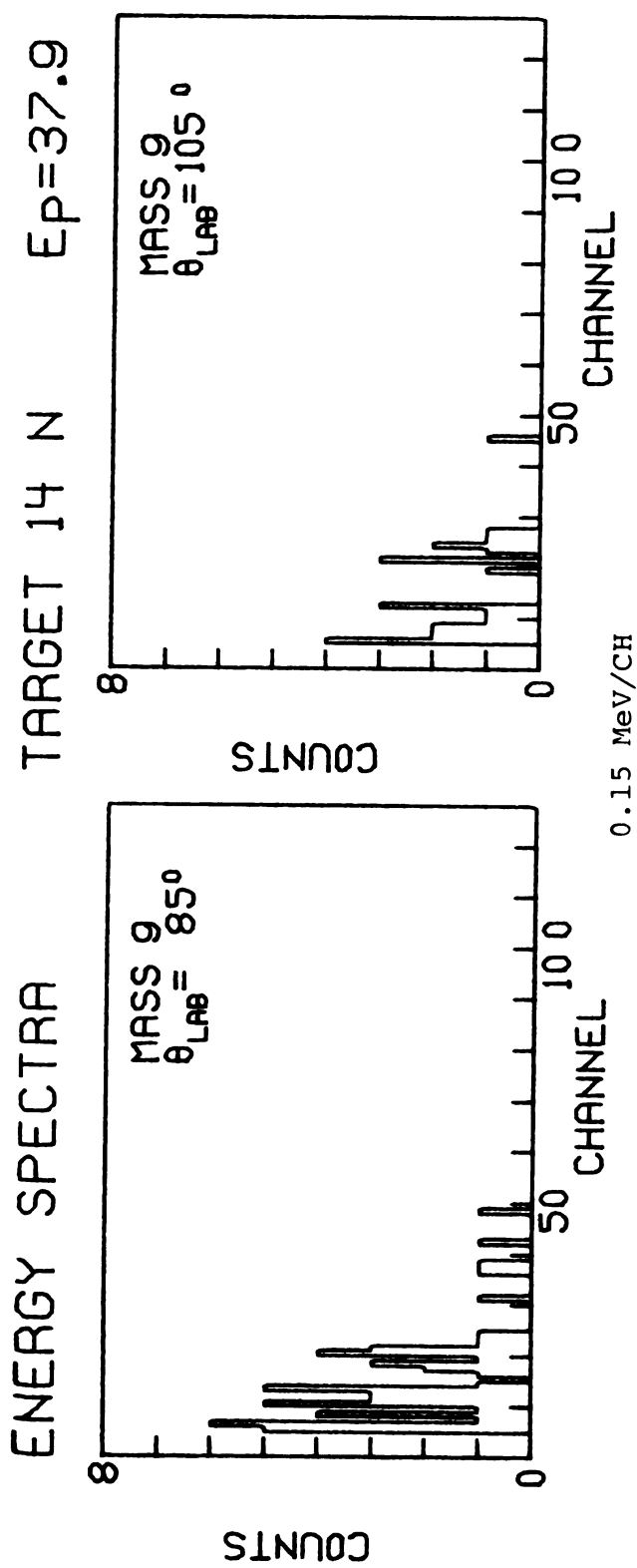


Figure 11. (continued)

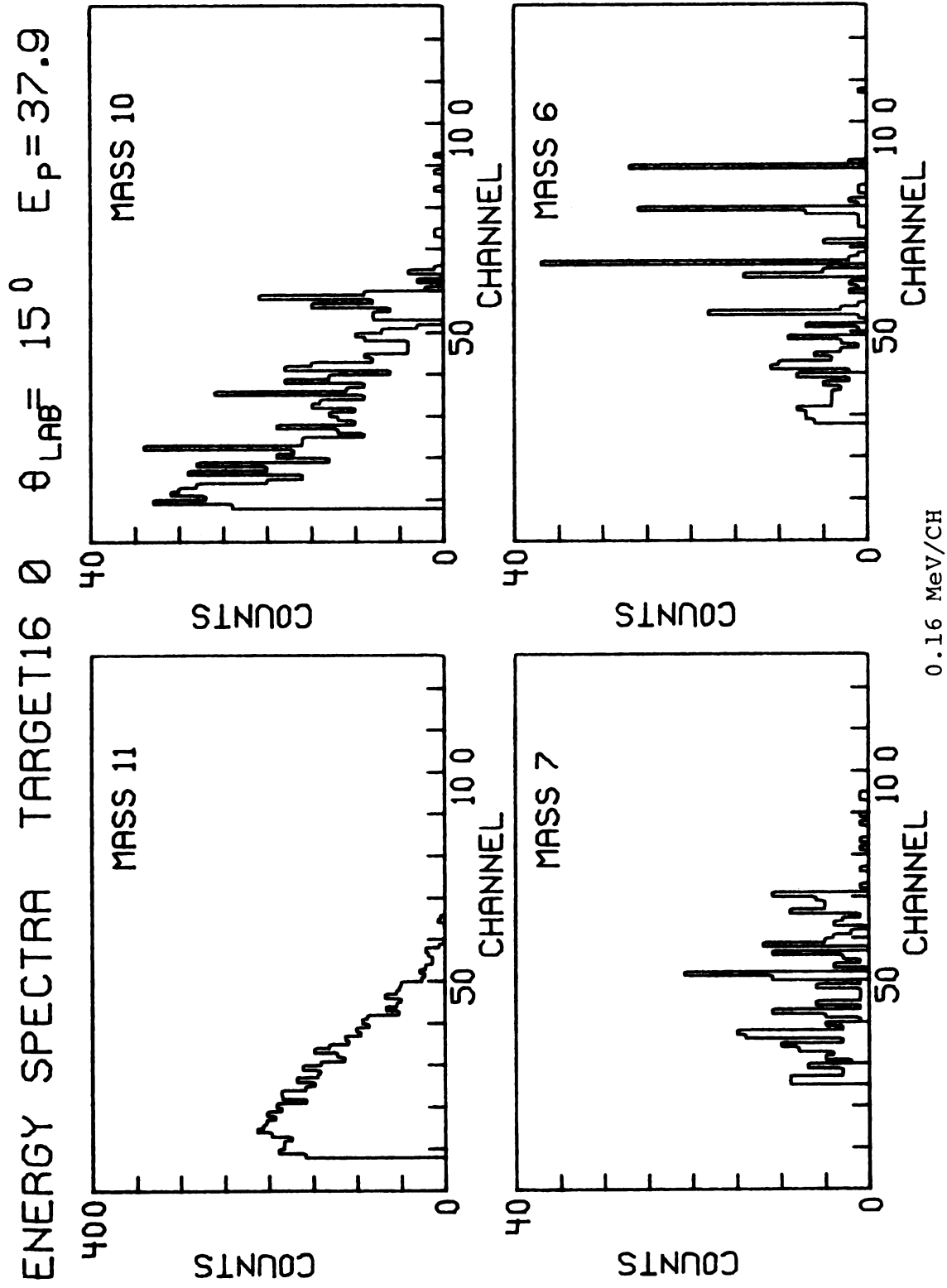


Figure 11. (continued)

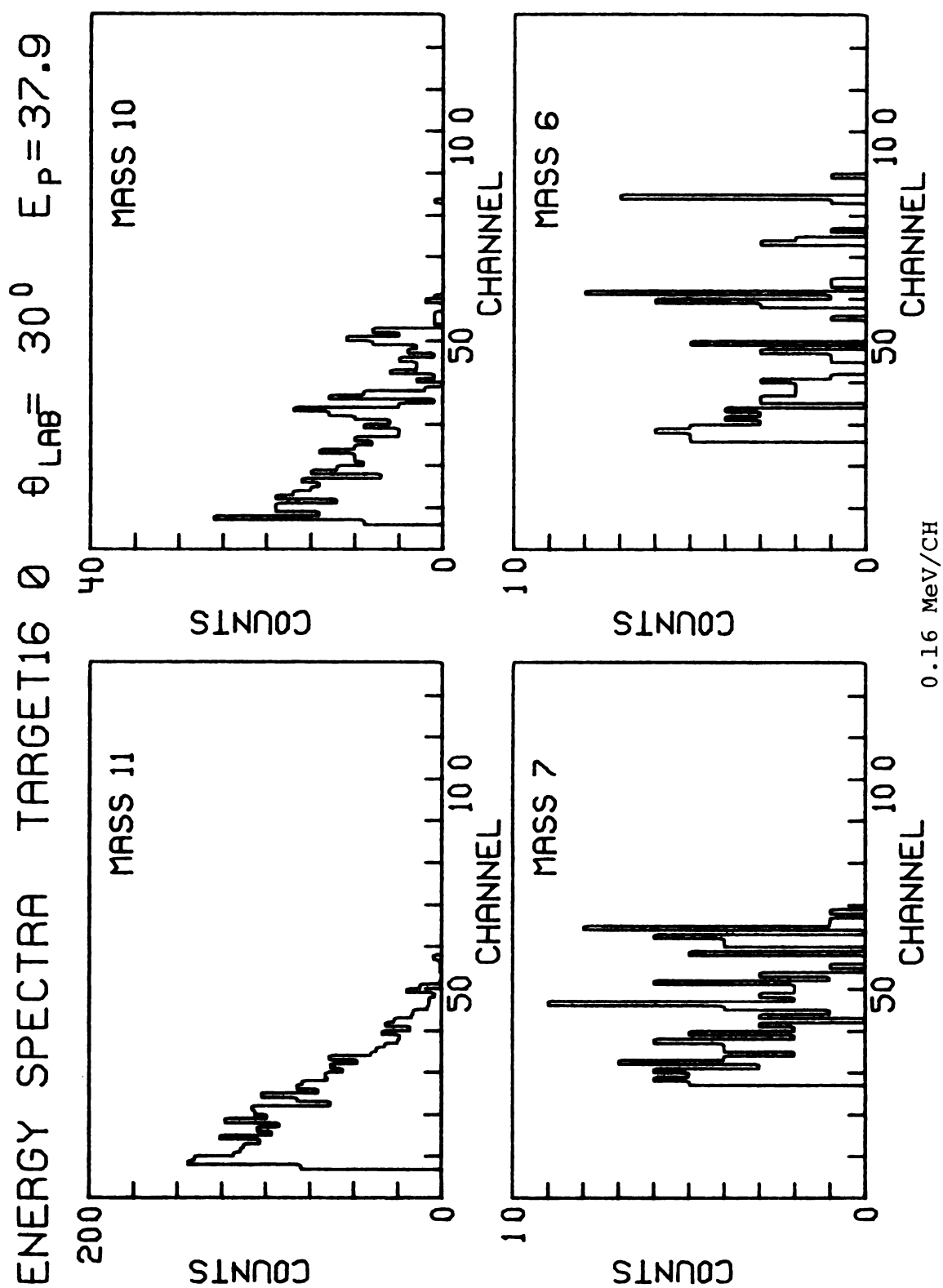


Figure 11. (continued)

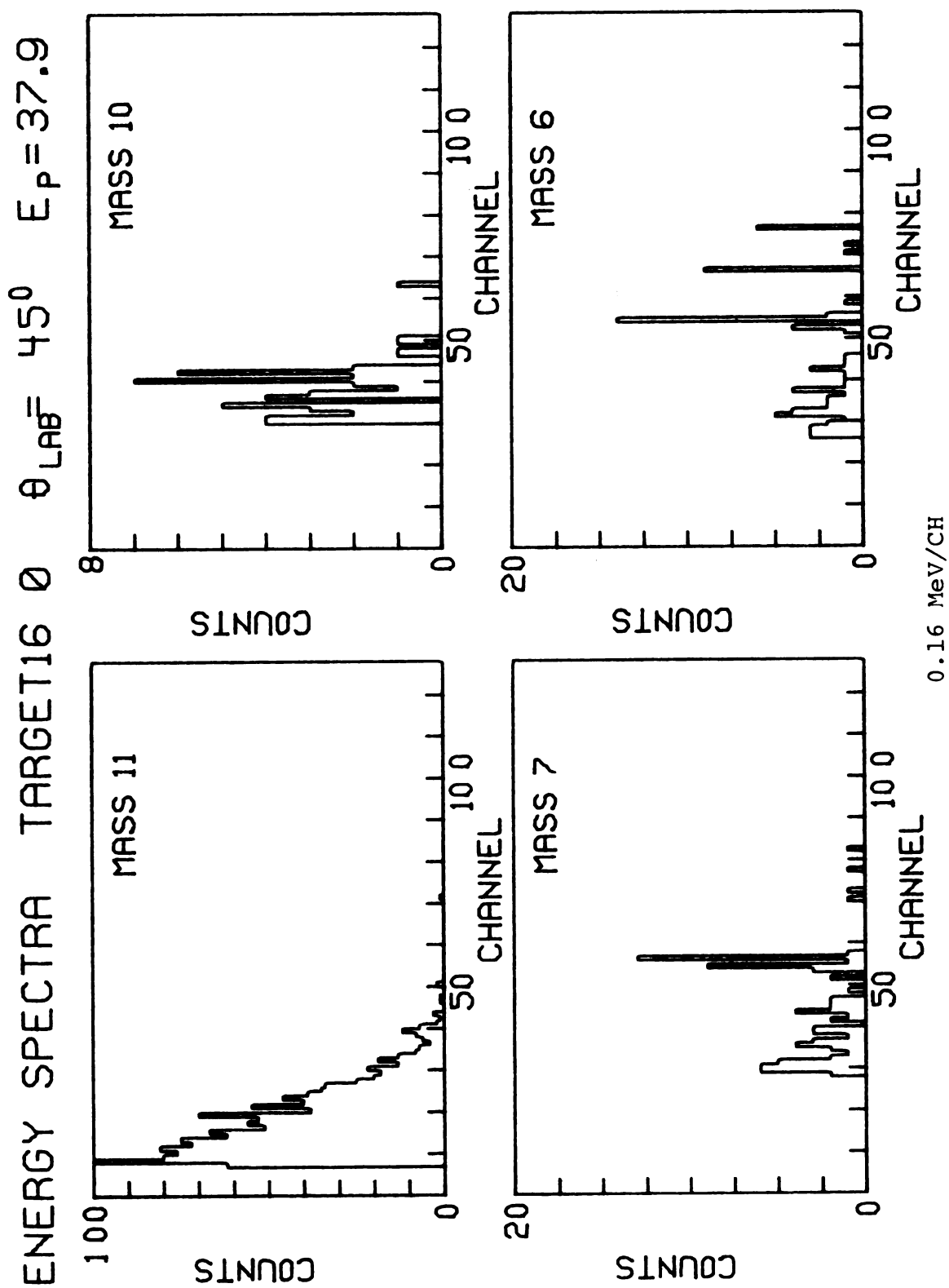


Figure 11. (continued)

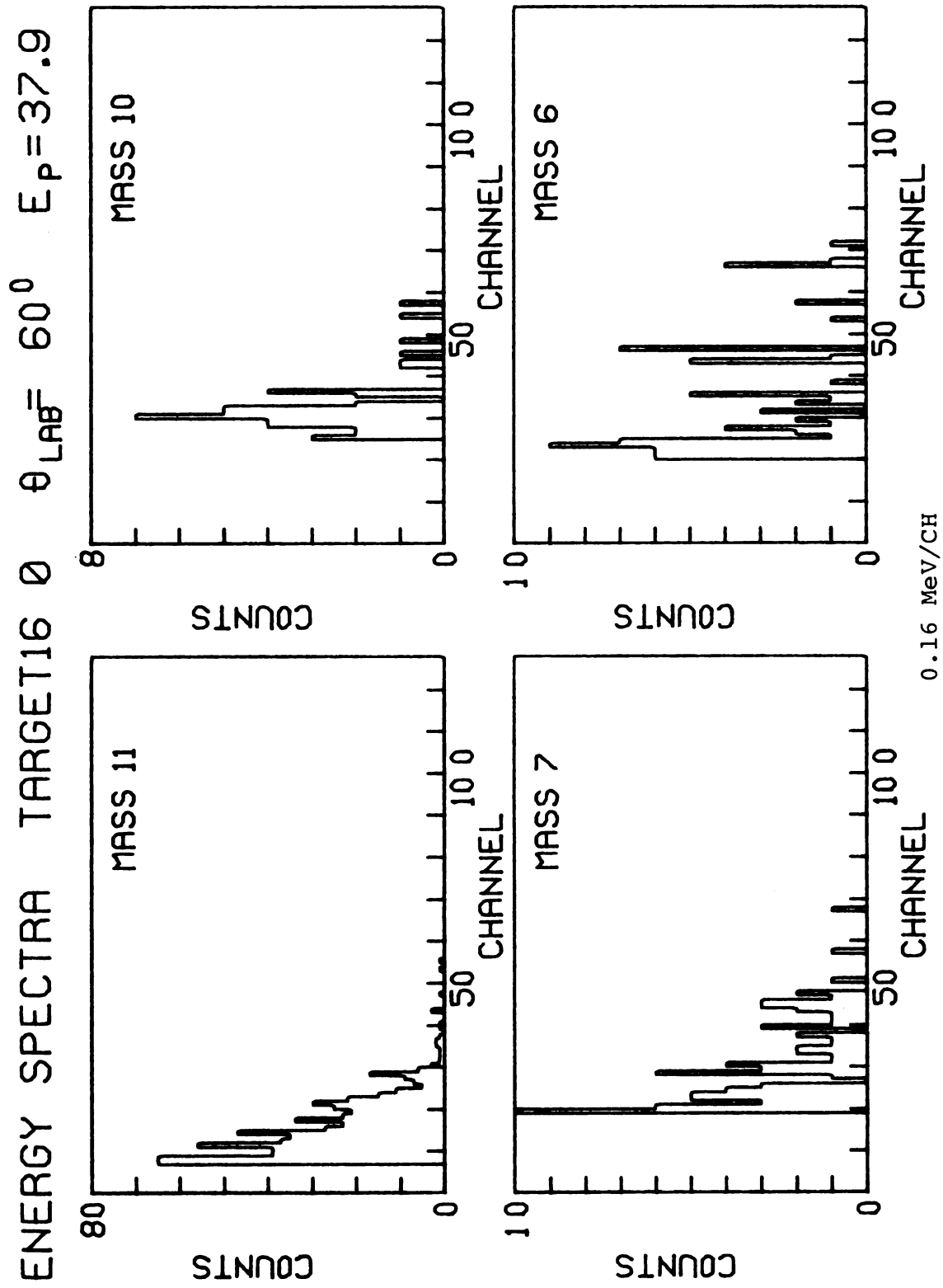


Figure 11. (continued)

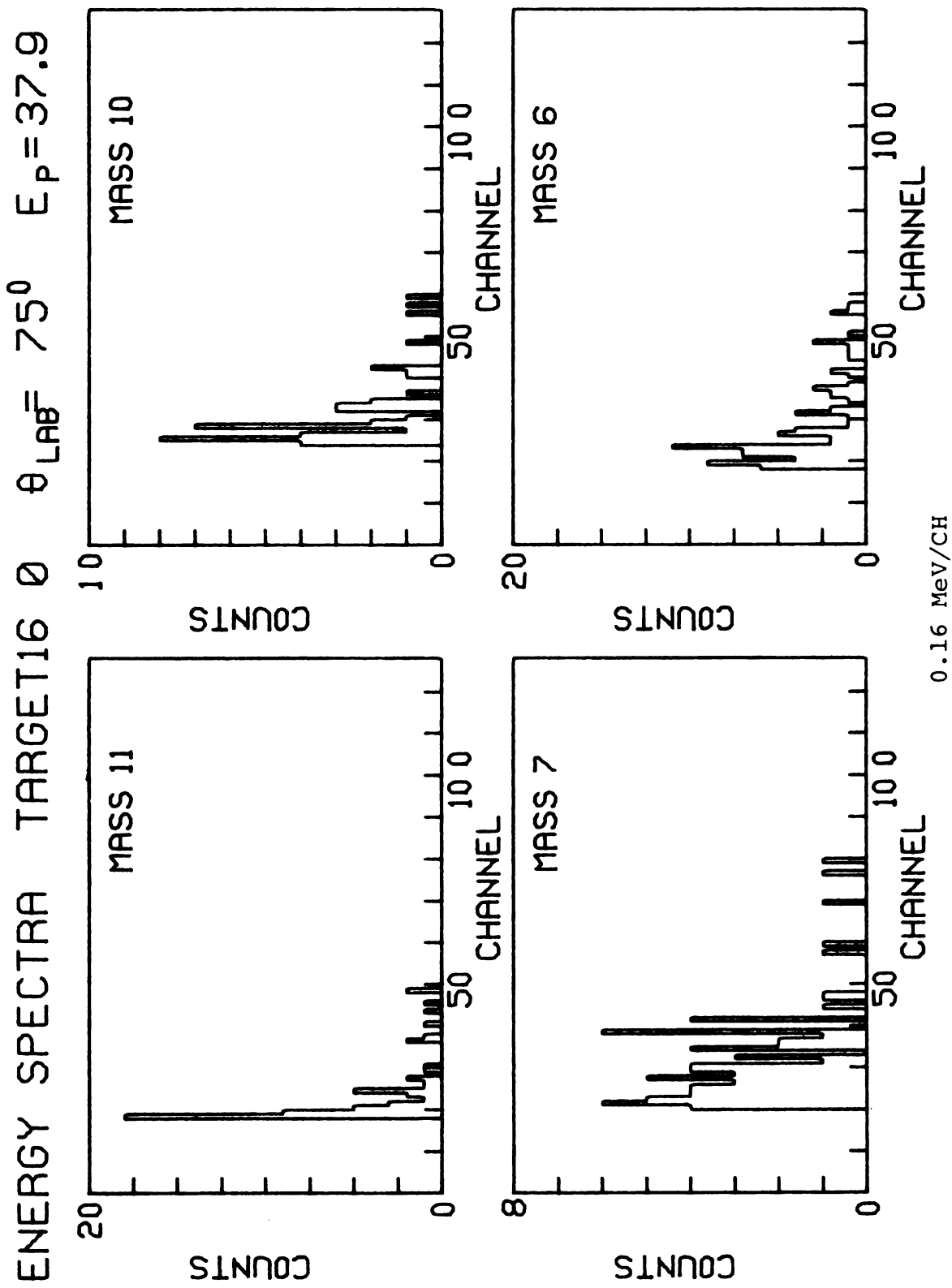


Figure 11. (continued)

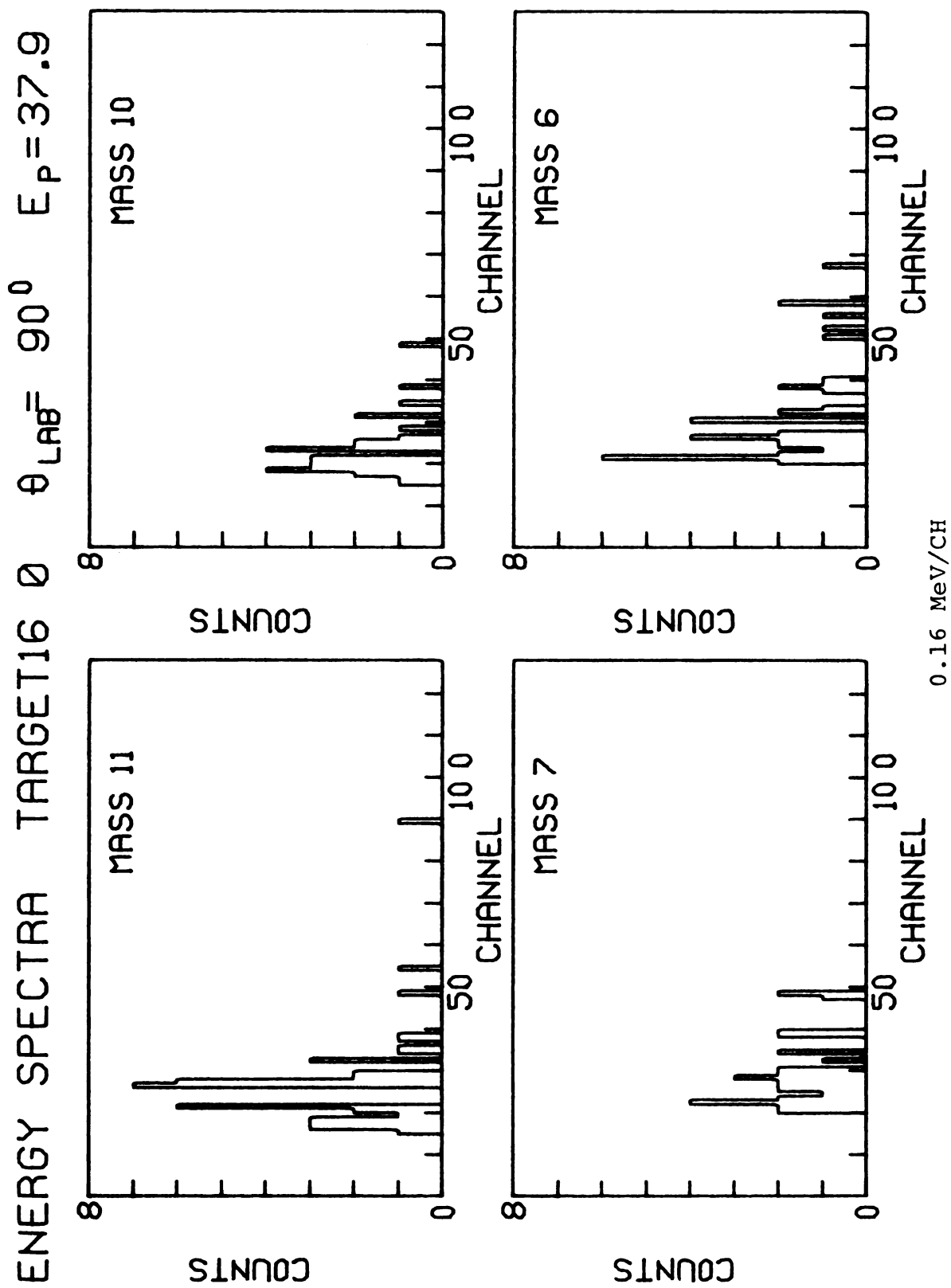


Figure 11. (continued)

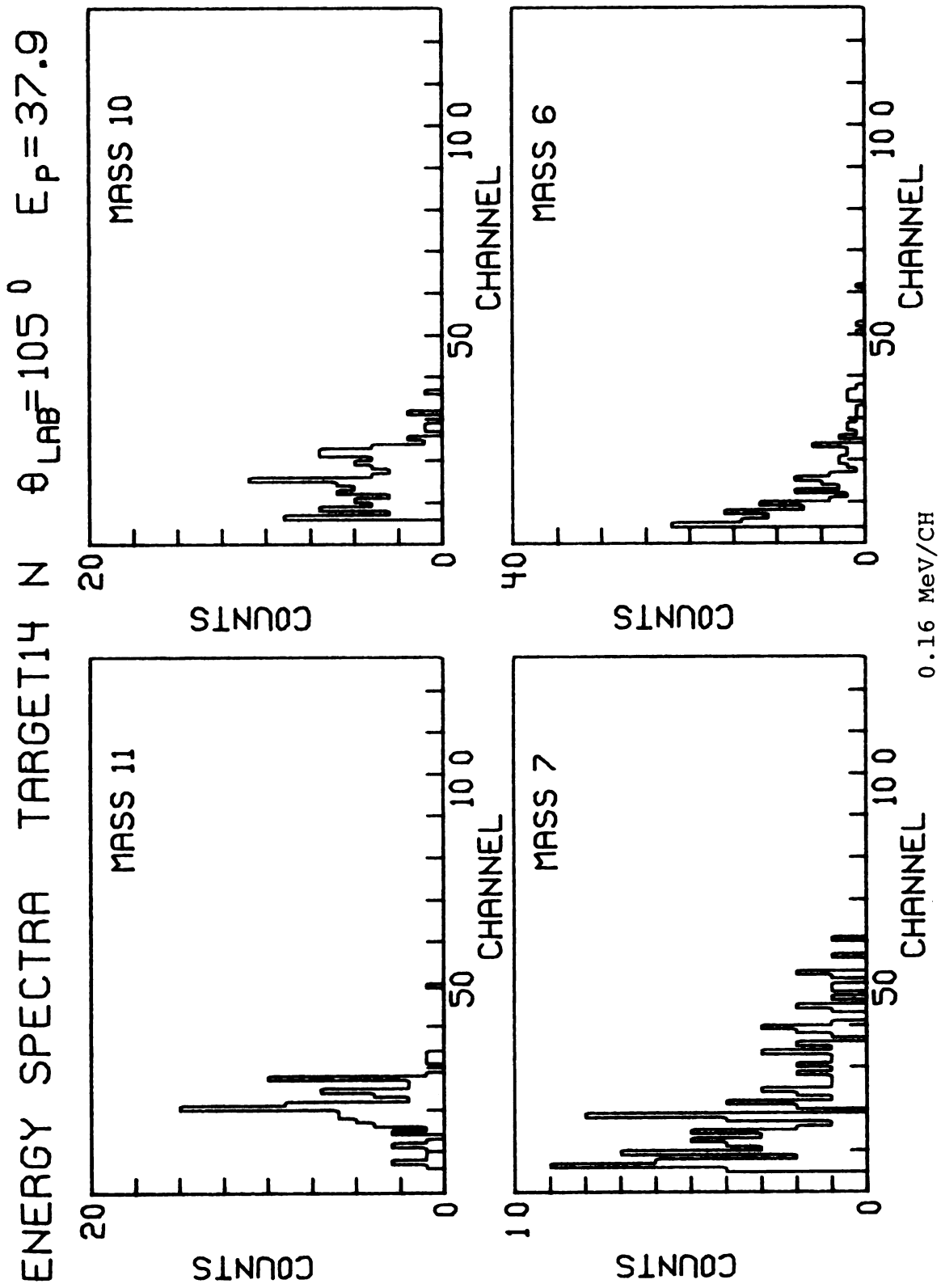


Figure 11. (continued)

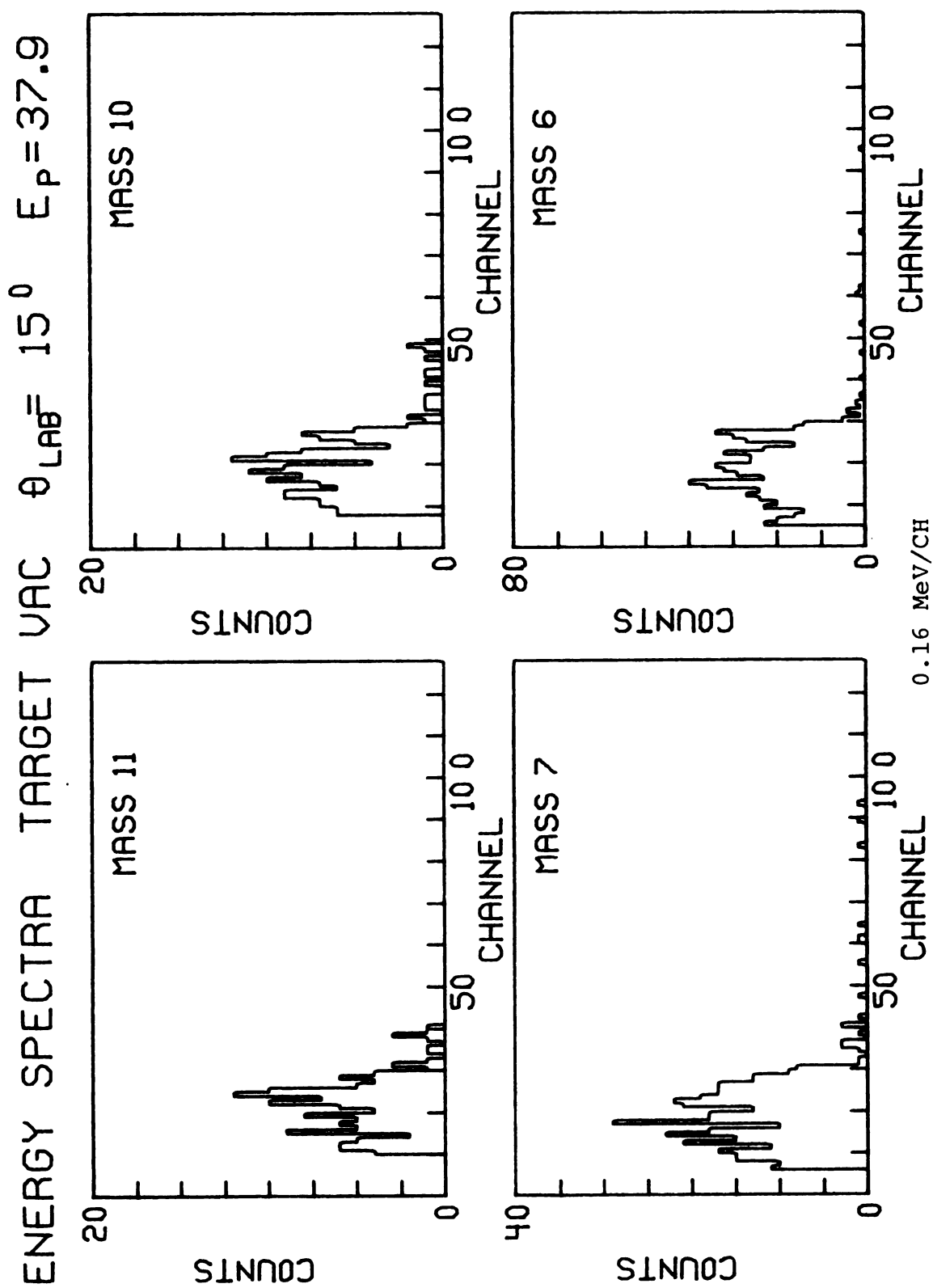


Figure 11. (continued)

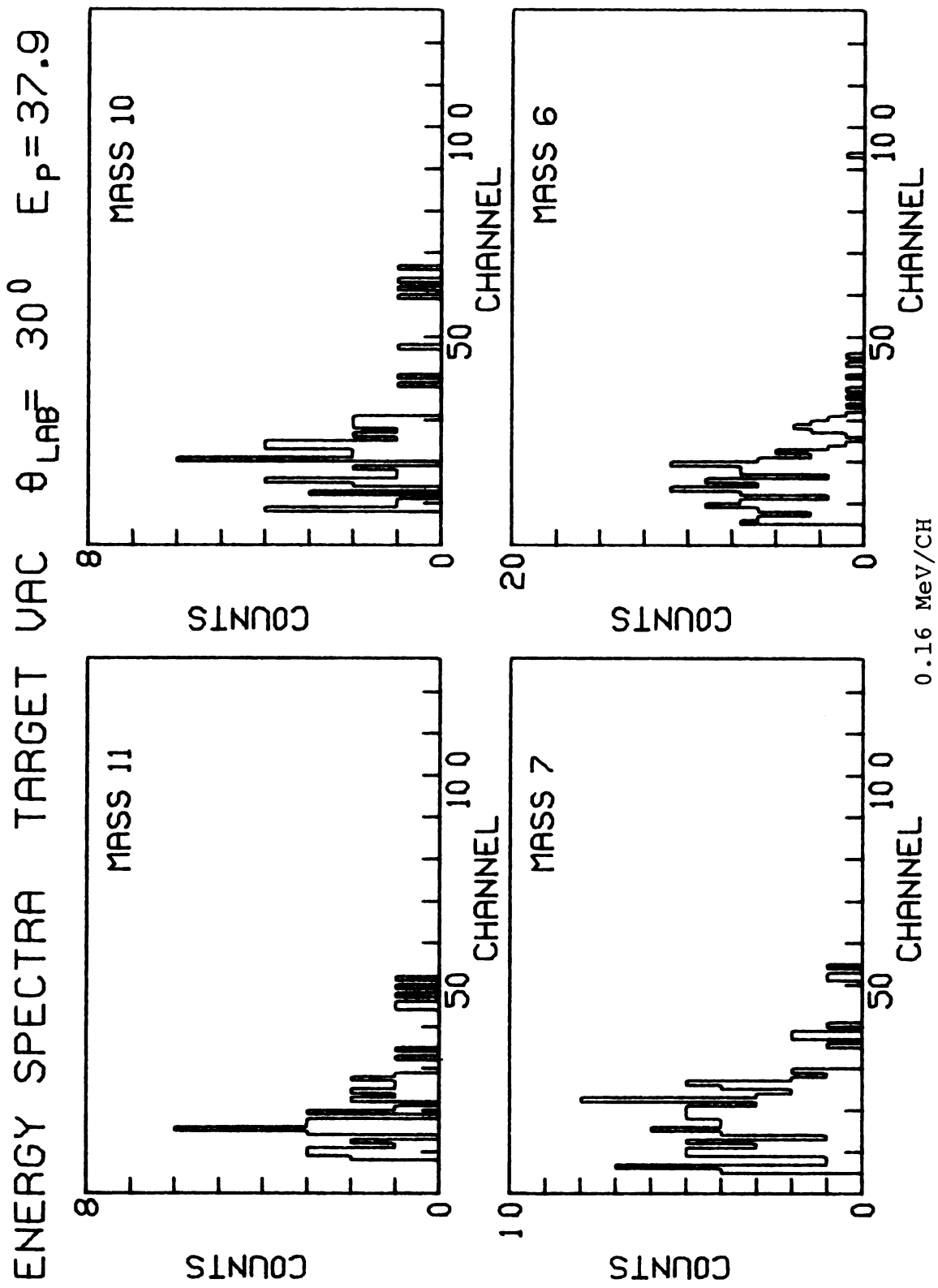
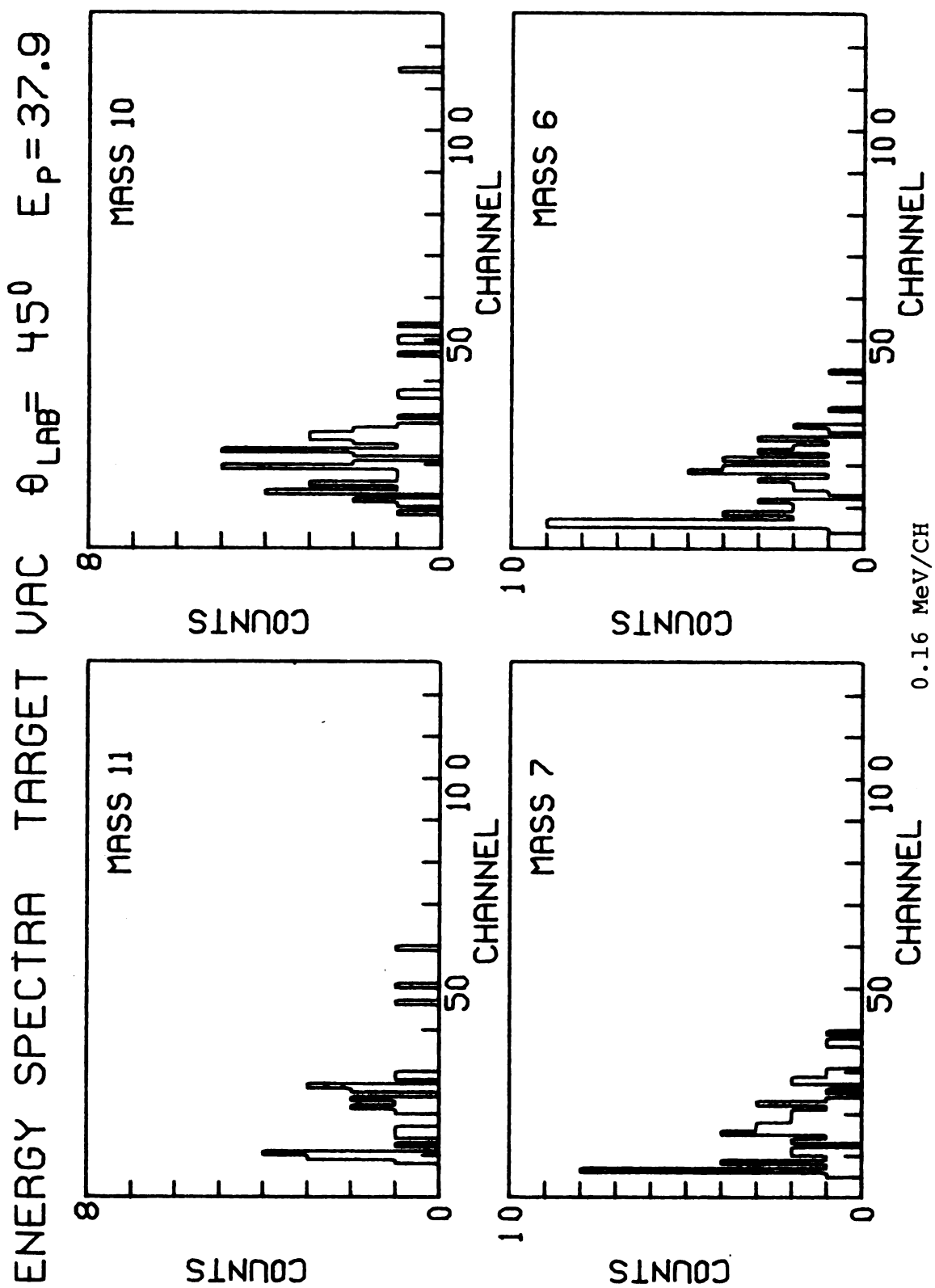


Figure 11. (continued)



ENERGY SPECTRA TARGET VAC $\theta_{\text{LAB}} = 60^\circ$ $E_p = 37.9$
 Figure 11. (continued)

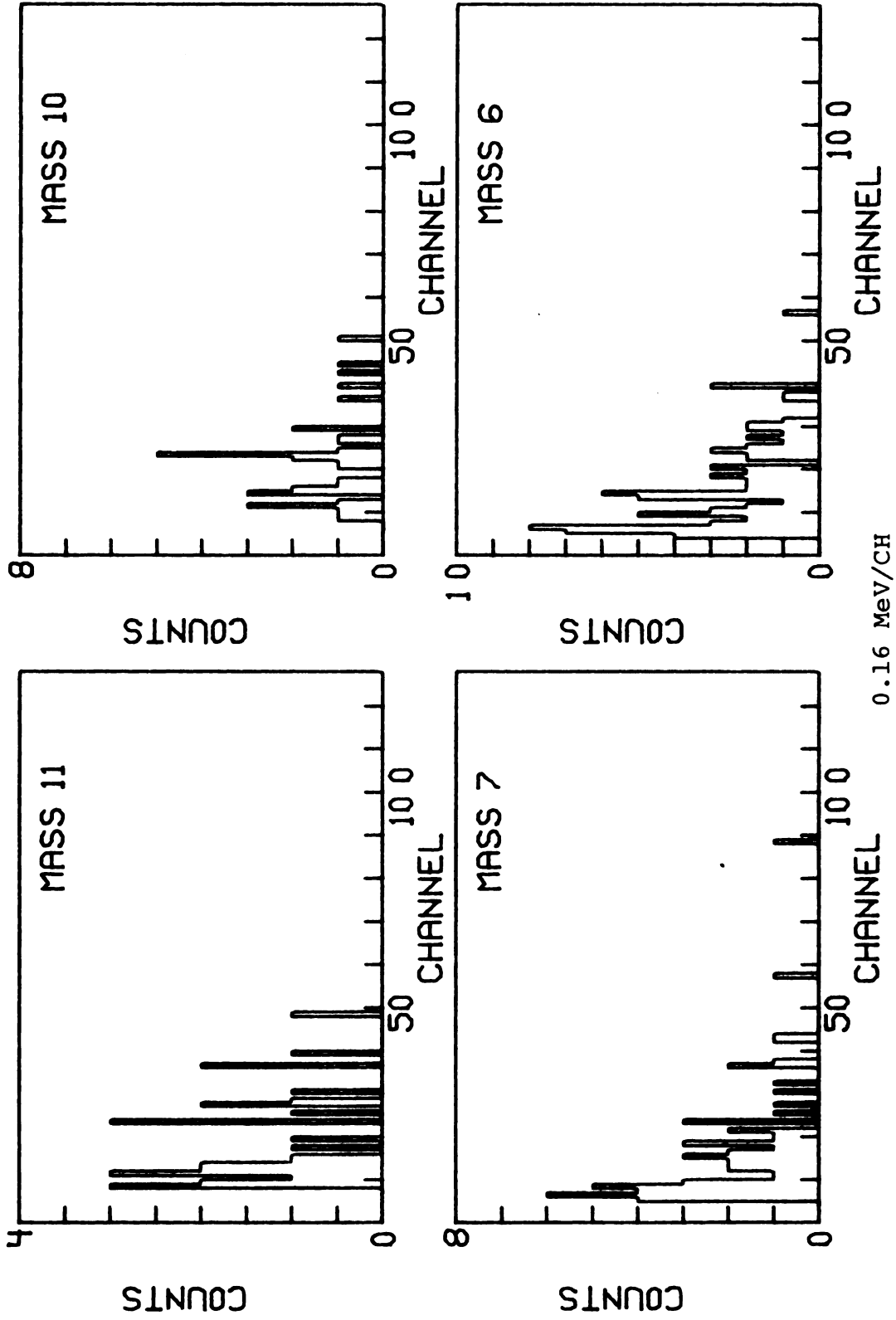
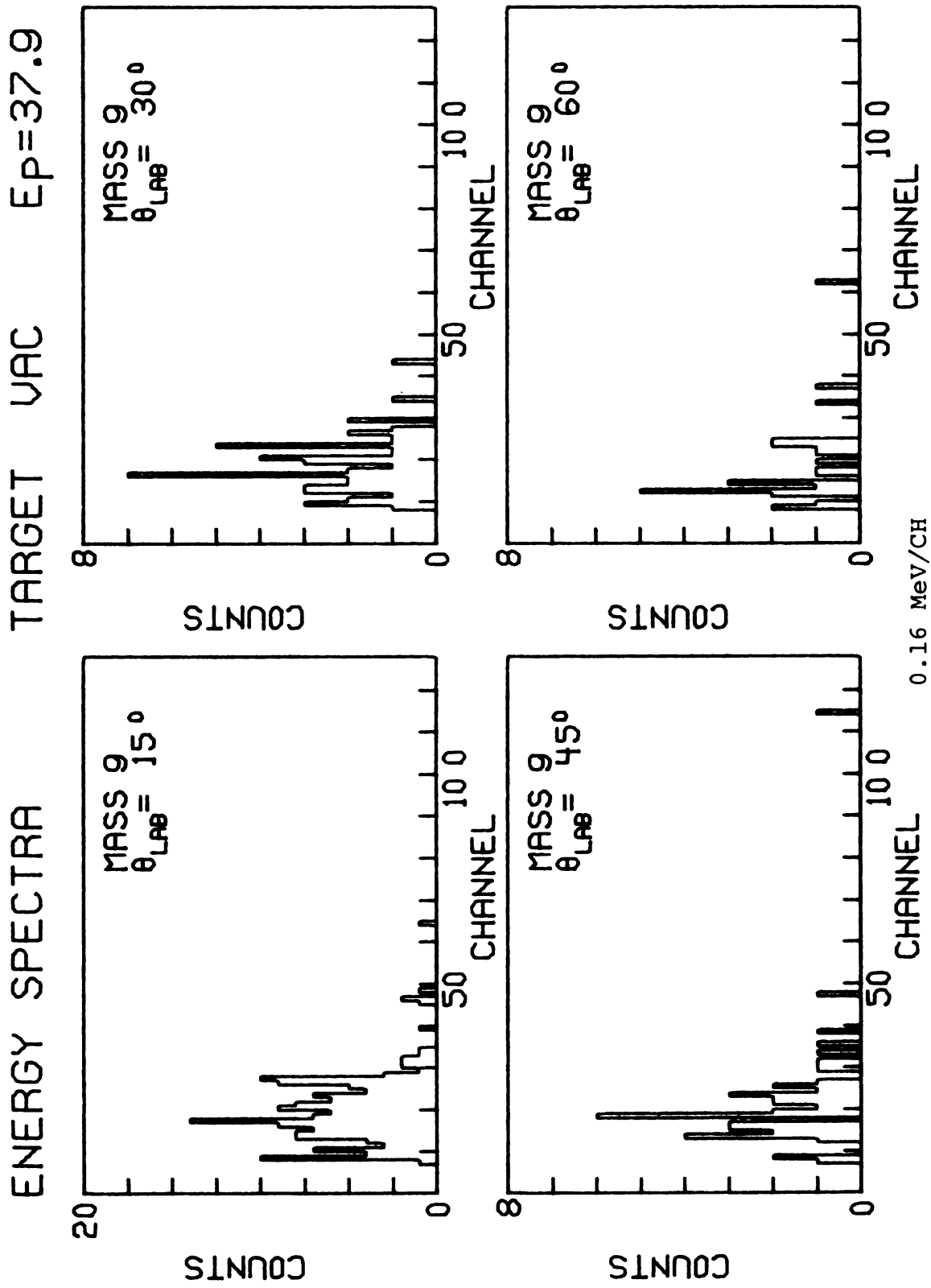


Figure 11. (continued)



RF period is longer at low beam energy). To account for energy losses in gas and formvar window a formula for stopping power from (SE 68) modified from a theory by Lindhard et al. (LS 61) is used:

$$(dE/dR) \text{ MeVcm}^2/\text{g} = \frac{7.39 \times 10^4 z_1^{1.207} z_2}{A_2 (z_1^{2/3} + z_2^{2/3})^{3/2}} \epsilon^{1/2}$$

z_1 = atomic number of projectile

z_2 = atomic number of target

A_2 = atomic weight of target

ϵ = the specific energy of the projectile in MeV/nucleon

Experimental stopping power data of carbon on carbon (NO 63) is compared to the values obtained by this formula in Table 5.

Table 5. Validity of stopping power equation

Stopping power of Carbon on Carbon (MeVcm ² /g)		
(Z ₁ =6, Z ₂ =6, A ₂ =12)		
	$\epsilon = 0.01$	$\epsilon = 0.1$
Experimental	1870	5760
Calculated	1890	5980

In the calculations for projectile energy loss it is assumed that ϵ , the energy per nucleon, is 0.1. This is valid since the energy cutoff for mass 6 is near 0.5 MeV and for mass 11 it is near 1 MeV. As explained in section 2.3.3 reaction products traverse varying areal densities of gas depending on detection angle, hence the low energy cutoff also depends on angle. Table 6 summarizes the range

of the cutoff effects. In Appendix G some more details of the calculations can be found.

The front surface electrode of the detector is a $40 \mu\text{g}/\text{cm}^2$ gold layer; the energy loss it causes is negligible as shown in table 6, and since the time cutoff limit is usually above the detector sensitivity limit, it has no effect on particle detection.

Table 6. Energy cutoff limits

		Energy in MeV	
Product ion:		${}^6\text{Li}$	${}^{11}\text{C}$
Minimum cutoff due to finite beam burst spacing	$E_p=22\text{MeV}$	0.3	0.6
	$E_p=42\text{MeV}$	0.5	0.9
energy loss in exit window	15° detection angle	0.4	0.7
	90° detection angle	0.2	0.3
energy loss in gold electrode of detector		0.02	0.03

The number of channels which the energy loss in the exit window represents is added to the number of channels for the low energy cutoff obtained from the energy spectra. The energy calibration curve necessary for determining the energy/channel ratio is determined from the two-body final state peaks appearing in the energy spectra. A low energy cutoff correction is performed by multiplying the number of cutoff-channels by a weighted average (60:30:10) of the number of events in the last three low energy channels of the energy

spectrum. The resulting number is added to the total number of counts in the spectrum and this represents the yield Y . One-half of the low energy extrapolation contribution is assigned as error. The justification for the low energy extrapolation and error assignment is that phase space considerations (see Sternheimer (ST 63) for example) for multiparticle breakup assure that the energy spectra show zero yield at zero particle energy.

4.2 Time-of-Flight cross-section calculation

The equation relating differential cross-section and yield at a specific angle is:

$$d\sigma/d\Omega = Y/n_i n_t \Delta\Omega .$$

Y = yield in counts.

n_i = no. of beam particles.

n_t = no. of target atoms/cm² traversed by beam as seen from detector

$\Delta\Omega$ = solid angle subtended by aperture S1 in steradians

Y is found by summing the events recorded in the 128 channels of an energy spectrum and adding the energy cutoff extrapolation as outlined in 4.1.

$$n_i = Q/(1.6 \times 10^{-19})$$

$Q(\text{coul})$ is the integrated charge.

$$n_t = \frac{2 \times S_2 \times R}{H \sin \theta} \times \frac{273.1}{T} \times P \times 2.687 \times 10^{19} .$$

This is an approximation, but for our geometry the maximum

error introduced is less than 0.02% (shown by comparison with the program G-FACTOR based on (SI 59) and written by Dr. R. A. Paddock at the M.S.U. Cyclotron laboratory).

$S_2(\text{cm})$ is the front slit width,

$R(\text{cm})$ is the average flight distance to S_1 ,

$H(\text{cm})$ is the distance between S_1 and S_2 ,

$\theta(\text{deg})$ is the angle between particle trajectory and
proton beam axis,

$T(^{\circ}\text{K})$ is the gas temperature,

$P(\text{atm})$ is the gas pressure.

The factor of 2 enters since N and O are diatomic gases.

$$\Delta\Omega = \frac{A}{R^2}$$

$A(\text{cm}^2)$ is the area of aperture S_1 ,

$R(\text{cm})$ as above.

Once $\frac{d\sigma}{d\Omega}$ is known at all angles, the total cross-section is obtained from

$$\sigma = 2\pi \int (d\sigma/d\Omega) \sin\theta d\theta$$

In the actual experiment performed $\frac{d\sigma}{d\Omega}$ is measured only at a few angles A_i . To perform the integration some arbitrary method must be chosen to fill in the missing points.

Given $\frac{d\sigma}{d\Omega}(A_i)$, it was assumed $\frac{d\sigma}{d\Omega}(\theta) = \frac{d\sigma}{d\Omega}(A_i)$ for θ in the range

$$(A_i + A_{i-1})/2 < \theta < (A_{i+1} + A_i)/2 .$$

There was always a maximum angle, A_{max} , beyond which no data could be obtained because of the low energy cutoff.

Depending on the behavior of the angular distribution for $A_{\max} < \theta \leq 180^\circ$, $\frac{d\sigma}{d\Omega}(\theta)$ was either assumed to be equal to $\frac{d\sigma}{d\Omega}(A_{\max})$ or it was assumed to go linearly to 0. Similarly for $0 < \theta < A_{\min}$, $\frac{d\sigma}{d\Omega}(\theta) = \frac{d\sigma}{d\Omega}(A_{\min})$ was assumed; no large error contribution is expected from this source except possibly for mass 11 at 26 MeV or below where the mass 11 yield is comprised largely or entirely of 2-body-final-state breakup. A modification of the $\frac{d\sigma}{d\Omega}(\theta) = \frac{d\sigma}{d\Omega}(A_{\max})$ extrapolation, taking account of peaks falling below the low energy cutoff, was used for these cases.

All angular distributions used in calculating total cross-sections are shown in Figure 12, p. 115. A fortran program was written to carry out the total cross-section calculations. Basic equations in the program are shown in Appendix G. Table 8 presents individual cross-section calculations. Table 9 and Figure 13 summarize all cross-sections measured. Table 10 reproduces the cross-sections from ^{12}C published in (DLA 70).

The abbreviations in Table 8 stand for:

N = number of monitor counts for calibration run,

P = pressure for calibration run,

Q = integrated charge in coulombs $\times 10^{-4}$,

H = distance between S1 and S2,

R = distance from S1 to the center of the cell,

B = width of front slit S2.

Lab angle: angle at which data was taken (θ),

Diff. Cross Sect. gives the calculated differential cross section at the angle given in the same row (mb/sr),

Contrib. to total cross sect. gives the result of the
 integration step from $(A_{i-1}+A_i)/2 \leq \theta \leq (A_{i+1}+A_i)/2$ (mb),
Assigned error: error due to low energy cutoff and the
 statistical error combined in quadrature (mb),
Yield is obtained from E spectra as explained in
 section 4.2 (counts),
Low E corr.: the low energy cutoff correction as explained
 in section 4.1 (counts),
Monitor counts: the events in the elastic proton peak
 of the cesium iodide detector used to integrate
 beam current and particle density,
Far: yield from extrapolation of integration to $\theta=0^\circ$ (mb),
Back: yield from extrapolation of integration to
 $\theta = 180^\circ$ (mb),
Total cross section: the result of the angular distribu-
 tion integration (mb).

The "total error" quoted in Table 8 is arrived at as follows: For each angle the statistical error of the yield and the low energy cutoff error are combined by their square. These are then added linearly, weighted by the contribution of the corresponding yield to the total cross-section. This conservative error estimate is used since all cutoff corrections may very well be in error in the same direction. The last value under the column "Assigned error" is the sum of these errors. One half of the back angle extrapolation and 0.2 of the extrapolation to $\theta=0$ are also added as error contributions. This final sum appears as the total error of

the cross-sections in the tables. Table 7 summarizes other error sources entering into the cross-section calculation.

Table 7. Error contribution not associated with particle detection.

Error Source	Error in %	Measuring Apparatus
A = area of back aperture S1	0.39	Traveling Microscope
S2 front slit width	1.2 to 1.7	Feeler gauge
R the average particle flight distance to S1	1.0	Steel rule and micro-meter (sensitive to beam centering)
H distance between S1 and S2	0.3	Steel rule and micro-meter
T temperature	0.7	Thermometer
T temperature (beam heating)	1.5	
P gas pressure	.33	Oil manometer
P gas pressure	.7	Aneroid gauge
Q integrated charge	2.0	Elcor A310B current integrator

Added in quadrature these error contributions yield:

$$\sqrt{\sum E_i^2} = 3.3\%.$$

When folded in with the smallest "total error" appearing in Table 8, namely 8.0%, the probable error becomes 8.7%. Hence these error contributions are negligible compared to the low energy cutoff correction.

Table 8. Individual Cross-Section Calculations for ^{14}N
and ^{16}O Targets.

14 N P SPALLATION CROSS SECTION FOR MASS 7 ; E=17.0 MEV

N= 15470 P=2.21CM HG Q=.765E 00 H=23.1CM R=24.7CM B=.109CM

LAB ANGLE	DIFF. CROSS SECT.	CONTRIB. TO TOTAL CROSS SECT.	ASSIGNED ERROR	YIELD	LOW E CORR.	MONITOR COUNTS
30.0	.682E 01	.739E 01	.132E 01	2018	1111	15470
45.0	.622E 01	.722E 01	.162E 01	1380	1125	18905
60.0	.398E 01	.565E 01	.135E 01	689	627	18875
75.0	.290E 01	.460E 01	.125E 01	295	349	14011
FOR		.146E 01	.260E 00			
BACK		.103E 02	.281E 01			
		-----	-----			
		.366E 02	.861E 01			

TOTAL CROSS SECTION = 36.6 MB \pm 14.1 MB (TOTAL ERROR=38 %)

14 N P SPALLATION CROSS SECTION FOR MASS 10 ; E=17.0 MEV

N= 15470 P=2.21CM HG Q=.765E 00 H=23.1CM R=24.7CM B=.109CM

LAB ANGLE	DIFF. CROSS SECT.	CONTRIB. TO TOTAL CROSS SECT.	ASSIGNED ERROR	YIELD	LOW E CORR.	MONITOR COUNTS
30.0	.133E 02	.144E 02	.554E 01	1418	4693	15470
45.0	.372E 01	.431E 01	.172E 01	306	1190	18905
60.0	.129E 01	.183E 01	.489E 00	201	226	18875
75.0	.582E 00	.922E 00	.232E 00	66	63	14011
FOR		.285E 01	.109E 01			
BACK		.207E 01	.521E 00			
		-----	-----			
		.264E 02	.959E 01			

TOTAL CROSS SECTION = 26.4 MB \pm 11.2 MB (TOTAL ERROR=42 %)

Table 8. (continued)

14 N P SPALLATION CROSS SECTION FOR MASS 11 ; E=17.0 MEV

N= 15470 P=2.21CM HG Q=.765E 00 H=23.1CM R=24.7CM B=.109CM

LAB ANGLE	DIFF. CROSS SECT.	CONTRIB. TO TOTAL CROSS SECT.	ASSIGNED ERROR	YIELD	LOW E CORR.	MONITOR COUNTS
30.0	.110E 02	.120E 02	.168E 00	5039	27	15470
45.0	.736E 01	.854E 01	.158E 00	2947	18	18905
60.0	.720E 01	.102E 02	.208E 00	2371	12	18875
75.0	.401E 01	.635E 01	.212E 00	875	13	14011
FOR		.236E 01	.332E-01			
BACK		.284E 02	.952E 00			
		-----	-----			
		.679E 02	.173E 01			

TOTAL CROSS SECTION = 67.9 MB ± 16.4 MB (TOTAL ERROR=24 %)

14 N P SPALLATION CROSS SECTION FOR MASS 6 ; E=21.7 MEV

N= 431392 P=2.21CM HG Q=.510E 01 H=23.1CM R=24.7CM B=.109CM

LAB ANGLE	DIFF. CROSS SECT.	CONTRIB. TO TOTAL CROSS SECT.	ASSIGNED ERROR	YIELD	LOW E CORR.	MONITOR COUNTS
15.0	.130E 01	.553E 00	.124E 00	481	390	50768
30.0	.108E 01	.883E 00	.211E 00	257	230	63776
45.0	.419E 00	.486E 00	.876E-01	91	46	64291
60.0	.232E 00	.330E 00	.574E-01	47	20	68914
75.0	.196E 00	.310E 00	.537E-01	36	11	63497
90.0	.162E 00	.265E 00	.519E-01	27	11	63962
105.0	.512E-01	.812E-01	.221E-01	11	0	56184
FOR		.700E-01	.158E-01			
BACK		.993E-01	.271E-01			
		-----	-----			
		.308E 01	.651E 00			

TOTAL CROSS SECTION = 3.1 MB ± .7 MB (TOTAL ERROR=23 %)

Table 8. (continued)

14 N P SPALLATION CROSS SECTION FOR MASS 7 ; E=21.7 MEV

N= 431392 P=2.21CM HG Q=.510E 01 H=23.1CM R=24.7CM B=.109CM

LAB ANGLE	DIFF. CROSS SECT.	CONTRIB. TO TOTAL CROSS SECT.	ASSIGNED ERROR	YIELD	LOW E CERR.	MONITOR COUNTS
15.0	.113E 02	.479E 01	.462E 00	6099	1447	50768
30.0	.846E 01	.694E 01	.552E 00	3226	598	63776
45.0	.643E 01	.745E 01	.811E 00	1652	450	64291
60.0	.463E 01	.658E 01	.743E 00	1042	295	68914
75.0	.304E 01	.481E 01	.652E 00	537	192	63497
90.0	.210E 01	.344E 01	.508E 00	352	141	63962
105.0	.186E 01	.294E 01	.690E 00	214	185	56184
FOR		.607E 00	.585E-01			
BACK		.360E 01	.845E 00			
		-----	-----			
		.412E 02	.532E 01			

TOTAL CROSS SECTION = 41.2 MB ± 7.2 MB (TOTAL ERROR=18 %)

14 N P SPALLATION CROSS SECTION FOR MASS 10 ; E=21.7 MEV

N= 431392 P=2.21CM HG Q=.510E 01 H=23.1CM R=24.7CM B=.109CM

LAB ANGLE	DIFF. CROSS SECT.	CONTRIB. TO TOTAL CROSS SECT.	ASSIGNED ERROR	YIELD	LOW E CERR.	MONITOR COUNTS
15.0	.306E 02	.130E 02	.233E 01	13125	7323	50768
30.0	.219E 02	.179E 02	.334E 01	6205	3677	63776
45.0	.152E 02	.177E 02	.423E 01	2599	2383	64291
60.0	.745E 01	.106E 02	.297E 01	944	1206	68914
75.0	.458E-01	.726E-01	.198E-01	11	0	63497
90.0	.102E 00	.168E 00	.279E-01	24	0	63962
105.0	.466E-02	.738E-02	.738E-02	1	0	56184
FOR		.164E 01	.295E 00			
BACK		.903E-02	.903E-02			
		-----	-----			
		.611E 02	.132E 02			

TOTAL CROSS SECTION = 61.1 MB ± 13.6 MB (TOTAL ERROR=22 %)

Table 8. (continued)

14 N P SPALLATION CROSS SECTION FOR MASS 11 ; E=21.7 MEV

N= 431392 P=2.21CM HG Q=.510E 01 H=23.1CM R=24.7CM B=.109CM

LAB ANGLE	DIFF. CROSS SECT.	CONTRIB. TO TOTAL CROSS SECT.	ASSIGNED ERROR	YIELD	LOW E CORR.	MONITOR COUNTS
15.0	.485E 01	.206E 01	.386E-01	3197	47	50768
30.0	.411E 01	.337E 01	.829E-01	1821	36	63776
45.0	.322E 01	.373E 01	.122E 00	1022	30	64291
60.0	.275E 01	.390E 01	.142E 00	772	21	68914
75.0	.302E 01	.479E 01	.180E 00	709	16	63497
90.0	.268E 01	.440E 01	.173E 00	618	12	63962
105.0	.941E 00	.149E 01	.107E 00	189	13	56184
FOR		.261E 00	.488E-02			
BACK		.155E 02	.263E 00			
		-----	-----			
		.395E 02	.111E 01			

TOTAL CROSS SECTION = 39.5 MB ± 9.0 MB (TOTAL ERROR=23 %)

14 N P SPALLATION CROSS SECTION FOR MASS 6 ; E=25.8 MEV

N= 760607 P=4.27CM HG Q=.503E 01 H=26.9CM R=27.5CM B=.075CM

LAB ANGLE	DIFF. CROSS SECT.	CONTRIB. TO TOTAL CROSS SECT.	ASSIGNED ERROR	YIELD	LOW E CORR.	MONITOR COUNTS
15.0	.631E 01	.268E 01	.492E 00	917	527	30315
30.0	.448E 01	.368E 01	.589E 00	758	351	60967
45.0	.351E 01	.406E 01	.952E 00	322	280	59020
60.0	.156E 01	.221E 01	.452E 00	296	200	133142
75.0	.945E 00	.150E 01	.397E 00	177	196	182690
90.0	.580E 00	.111E 01	.328E 00	88	124	174110
110.0	.207E 00	.424E 00	.116E 00	33	37	150363
FOR		.339E 00	.623E-01			
BACK		.325E 00	.890E-01			
		-----	-----			
		.163E 02	.348E 01			

TOTAL CROSS SECTION = 16.3 MB ± 3.7 MB (TOTAL ERROR=23 %)

Table 8. (continued)

14 N P SPALLATION CROSS SECTION FOR MASS 7 ; E=25.8 MEV

N= 760607 P=4.27CM HG Q=.503E 01 H=26.9CM R=27.5CM B=.075CM

LAB ANGLE	DIFF. CROSS SECT.	CONTRIB. TO TOTAL CROSS SECT.	ASSIGNED ERROR	YIELD	LOW E CERR.	MONITOR COUNTS
15.0	.559E 01	.237E 01	.186E 00	1089	189	30315
30.0	.482E 01	.396E 01	.486E 00	906	287	60967
45.0	.376E 01	.435E 01	.390E 00	539	106	59020
60.0	.305E 01	.434E 01	.472E 00	769	205	133142
75.0	.225E 01	.357E 01	.498E 00	646	243	182690
90.0	.160E 01	.305E 01	.522E 00	388	196	174110
110.0	.104E 01	.213E 01	.430E 00	212	139	150363
FOR		.300E 00	.235E 01			
BACK		.163E 01	.329E 00			
		-----	-----			
		.257E 02	.334E 01			

TOTAL CROSS SECTION = 25.7 MB \pm 4.2 MB (TOTAL ERROR=16 %)

14 N P SPALLATION CROSS SECTION FOR MASS 10 ; E=25.8 MEV

N= 760607 P=4.27CM HG Q=.503E 01 H=26.9CM R=27.5CM B=.075CM

LAB ANGLE	DIFF. CROSS SECT.	CONTRIB. TO TOTAL CROSS SECT.	ASSIGNED ERROR	YIELD	LOW E CERR.	MONITOR COUNTS
15.0	.237E 02	.101E 02	.126E 01	4069	1351	30315
30.0	.186E 02	.153E 02	.236E 01	3189	1417	60967
45.0	.126E 02	.146E 02	.278E 01	1347	820	59020
60.0	.730E 01	.104E 02	.250E 01	1208	1122	133142
75.0	.355E 01	.562E 01	.167E 01	571	831	182690
90.0	.160E 01	.306E 01	.111E 01	160	426	174110
110.0	.591E 01	.121E 00	.412E 01	7	13	150363
FOR		.127E 01	.159E 00			
BACK		.928E 01	.316E 01			
		-----	-----			
		.605E 02	.119E 02			

TOTAL CROSS SECTION = 60.5 MB \pm 12.2 MB (TOTAL ERROR=20 %)

Table 8. (continued)

14 N P SPALLATION CROSS SECTION FOR MASS 11 ; E=25.8 MEV

N= 760607 P=4.27CM HG Q=.503E 01 H=26.9CM R=27.5CM B=.075CM

LAB ANGLE	DIFF. CROSS SECT.	CONTRIB. TO TOTAL CROSS SECT.	ASSIGNED ERROR	YIELD	LOW E CORR.	MONITOR COUNTS
15.0	.404E 01	.171E 01	.198E 00	716	207	30315
30.0	.318E 01	.261E 01	.421E 00	537	250	60967
45.0	.272E 01	.315E 01	.536E 00	312	155	59020
60.0	.206E 01	.292E 01	.344E 00	508	148	133142
75.0	.166E 01	.263E 01	.247E 00	542	114	182690
90.0	.199E 01	.380E 01	.663E 00	476	250	174110
110.0	.110E 01	.226E 01	.569E 00	187	186	150363
FOR		.217E 00	.251E-01			
BACK		.346E 01	.872E 00			
		-----	-----			
		.228E 02	.387E 01			

TOTAL CROSS SECTION = 22.8 MB ± 5.6 MB (TOTAL ERROR=25 %)

14 N P SPALLATION CROSS SECTION FOR MASS 6 ; E=28.6 MEV

N=1026222 P=4.11CM HG Q=.748E 01 H=26.2CM R=27.6CM B=.076CM

LAB ANGLE	DIFF. CROSS SECT.	CONTRIB. TO TOTAL CROSS SECT.	ASSIGNED ERROR	YIELD	LOW E CORR.	MONITOR COUNTS
20.0	.647E 01	.248E 01	.639E-01	1479	12	32621
25.0	.649E 01	.150E 01	.955E-01	1278	170	39030
30.0	.639E 01	.376E 01	.236E 00	1638	219	62753
45.0	.407E 01	.472E 01	.415E 00	1153	235	103480
60.0	.265E 01	.376E 01	.420E 00	738	203	132042
75.0	.116E 01	.184E 01	.892E-01	454	18	168217
90.0	.777E 00	.127E 01	.116E 00	340	64	223078
105.0	.508E 00	.805E 00	.913E-01	223	57	228391
120.0	.480E 00	.682E 00	.141E 00	132	89	171014
FOR		.618E 00	.159E-01			
BACK		.590E 00	.122E 00			
		-----	-----			
		.220E 02	.181E 01			

TOTAL CROSS SECTION = 22.0 MB ± 2.2 MB (TOTAL ERROR=10 %)

Table 8. (continued)

14 N P SPALLATION CROSS SECTION FOR MASS 7 ; E=28.6 MEV

N=1026222 P=4.11CM HG Q=.748E 01 H=26.2CM R=27.6CM B=.076CM

LAB ANGLE	DIFF. CROSS SECT.	CONTRIB. TO TOTAL CROSS SECT.	ASSIGNED ERROR	YIELD	LOW E CORR.	MONITOR COUNTS
20.0	.350E 01	.134E 01	.569E-01	765	42	32621
25.0	.340E 01	.787E 00	.445E-01	690	68	39030
30.0	.316E 01	.186E 01	.103E 00	833	85	62753
45.0	.255E 01	.296E 01	.186E 00	775	95	103480
60.0	.204E 01	.290E 01	.242E 00	615	111	132042
75.0	.150E 01	.237E 01	.148E 00	547	60	168217
90.0	.118E 01	.194E 01	.158E 00	523	90	223078
105.0	.908E 00	.144E 01	.203E 00	364	136	228391
120.0	.600E 00	.852E 00	.914E-01	225	51	171014
FOR BACK		.334E 00	.142E-01			
		.737E 00	.790E-01			
		-----	-----			
		.175E 02	.133E 01			

TOTAL CROSS SECTION = 17.5 MB ± 1.8 MB (TOTAL ERROR=10 %)

14 N P SPALLATION CROSS SECTION FOR MASS 10 ; E=28.6 MEV

N=1026222 P=4.11CM HG Q=.748E 01 H=26.2CM R=27.6CM B=.076CM

LAB ANGLE	DIFF. CROSS SECT.	CONTRIB. TO TOTAL CROSS SECT.	ASSIGNED ERROR	YIELD	LOW E CORR.	MONITOR COUNTS
20.0	.182E 02	.695E 01	.364E 00	3761	421	32621
25.0	.175E 02	.405E 01	.372E 00	3196	707	39030
30.0	.159E 02	.935E 01	.687E 00	3954	667	62753
45.0	.101E 02	.117E 02	.103E 01	2833	597	103480
60.0	.691E 01	.982E 01	.138E 01	1768	687	132042
75.0	.391E 01	.620E 01	.119E 01	980	607	168217
90.0	.197E 01	.323E 01	.758E 00	547	478	223078
105.0	.120E 01	.190E 01	.588E 00	251	408	228391
120.0	.878E 00	.125E 01	.476E 00	96	308	171014
FOR BACK		.173E 01	.908E-01			
		.108E 01	.412E 00			
		-----	-----			
		.572E 02	.735E 01			

TOTAL CROSS SECTION = 57.2 MB ± 8.2 MB (TOTAL ERROR=14 %)

Table 8. (continued)

14 N P SPALLATION CROSS SECTION FOR MASS 11 ; E=28.6 MEV

N=1026222 P=4.11CM HG Q=.748E 01 H=26.2CM R=27.6CM B=.076CM

LAB ANGLE	DIFF. CROSS SECT.	CONTRIB. TO TOTAL CROSS SECT.	ASSIGNED ERROR	YIELD	LOW E CORR.	MONITOR COUNTS
20.0	.412E 01	.158E 01	.180E 00	740	210	32621
25.0	.712E 01	.165E 01	.360E 00	895	693	39030
30.0	.406E 01	.239E 01	.552E 00	637	543	62753
45.0	.195E 01	.227E 01	.395E 00	437	229	103480
60.0	.156E 01	.222E 01	.299E 00	411	144	132042
75.0	.128E 01	.203E 01	.119E 00	476	44	168217
90.0	.893E 00	.146E 01	.938E-01	420	44	223078
105.0	.109E 01	.173E 01	.317E 00	384	217	228391
120.0	.970E 00	.138E 01	.344E 00	225	221	171014
FOR		.394E 00	.449E-01			
BACK		.238E 01	.596E 00			
		-----	-----			
		.195E 02	.330E 01			

TOTAL CROSS SECTION = 19.5 MB ± 4.6 MB (TOTAL ERROR=23 %)

14 N P SPALLATION CROSS SECTION FOR MASS 6 ; E=31.9 MEV

N= 15704 P=5.36CM HG Q=.100E 00 H=25.7CM R=26.3CM B=.076CM

LAB ANGLE	DIFF. CROSS SECT.	CONTRIB. TO TOTAL CROSS SECT.	ASSIGNED ERROR	YIELD	LOW E CORR.	MONITOR COUNTS
15.0	.715E 01	.303E 01	.758E-01	2307	70	28419
30.0	.576E 01	.472E 01	.336E 00	1075	164	35519
45.0	.401E 01	.465E 01	.271E 00	2206	274	73288
60.0	.257E 01	.365E 01	.321E 00	504	96	71363
75.0	.180E 01	.285E 01	.231E 00	382	61	83930
90.0	.104E 01	.171E 01	.128E 00	282	35	107217
105.0	.585E 00	.927E 00	.824E-01	164	23	108880
120.0	.435E 00	.618E 00	.673E-01	123	23	102567
FOR		.384E 00	.960E-02			
BACK		.534E 00	.583E-01			
		-----	-----			
		.231E 02	.158E 01			

TOTAL CROSS SECTION = 23.1 MB ± 1.9 MB (TOTAL ERROR= 8 %)

Table 8. (continued)

14 N P SPALLATION CROSS SECTION FOR MASS 7 ; E=31.9 MEV

N= 15704 P=5.36CM HG Q=.100E 00 H=25.7CM R=26.3CM B=.076CM

LAB ANGLE	DIFF. CROSS SECT.	CONTRIB. TO TOTAL CROSS SECT.	ASSIGNED ERROR	YIELD	LOW E CORR.	MONITOR COUNTS
15.0	.263E 01	.112E 01	.557E-01	808	67	28419
30.0	.214E 01	.175E 01	.121E 00	411	49	35519
45.0	.178E 01	.207E 01	.163E 00	941	163	73288
60.0	.212E 01	.301E 01	.445E 00	353	142	71363
75.0	.144E 01	.228E 01	.271E 00	276	78	83930
90.0	.822E 00	.135E 01	.104E 00	226	24	107217
105.0	.720E 00	.114E 01	.102E 00	200	30	108880
120.0	.581E 00	.825E 00	.915E-01	159	36	102567
FOR BACK		.141E 00	.706E-02			
		.714E 00	.792E-01			
		-----	-----			
		.144E 02	.144E 01			

TOTAL CROSS SECTION = 14.4 MB ± 1.8 MB (TOTAL ERROR=13 %)

14 N P SPALLATION CROSS SECTION FOR MASS 10 ; E=31.9 MEV

N= 15704 P=5.36CM HG Q=.100E 00 H=25.7CM R=26.3CM B=.076CM

LAB ANGLE	DIFF. CROSS SECT.	CONTRIB. TO TOTAL CROSS SECT.	ASSIGNED ERROR	YIELD	LOW E CORR.	MONITOR COUNTS
15.0	.146E 02	.621E 01	.263E 00	4477	390	28419
30.0	.114E 02	.938E 01	.578E 00	2171	289	35519
45.0	.746E 01	.866E 01	.310E 00	4311	304	73288
60.0	.574E 01	.815E 01	.104E 01	1006	335	71363
75.0	.380E 01	.603E 01	.111E 01	594	343	83930
90.0	.214E 01	.351E 01	.789E 00	361	290	107217
105.0	.107E 01	.170E 01	.280E 00	234	109	108880
120.0	.554E 00	.787E 00	.154E 00	116	70	102567
FOR BACK		.787E 00	.333E-01			
		.681E 00	.133E 00			
		-----	-----			
		.459E 02	.469E 01			

TOTAL CROSS SECTION = 45.9 MB ± 5.2 MB (TOTAL ERROR=11 %)

Table 8. (continued)

14 N P SPALLATION CROSS SECTION FOR MASS 11 ; E=31.9 MEV

N= 15704 P=5.36CM HG Q=.100E 00 H=25.7CM R=26.3CM B=.076CM

LAB ANGLE	DIFF. CROSS SECT.	CONTRIB. TO TOTAL CROSS SECT.	ASSIGNED ERROR	YIELD	LOW E CORR.	MONITOR COUNTS
15.0	.572E 01	.243E 01	.405E 00	1271	631	28419
30.0	.648E 01	.532E 01	.124E 01	746	649	35519
45.0	.350E 01	.406E 01	.101E 01	1091	1074	73288
60.0	.178E 01	.252E 01	.422E 00	280	135	71363
75.0	.913E 00	.145E 01	.181E 00	175	50	83930
90.0	.697E 00	.114E 01	.107E 00	182	30	107217
105.0	.748E 00	.119E 01	.825E-01	221	18	108880
120.0	.101E 01	.143E 01	.309E 00	194	144	102567
FOR BACK		.307E 00	.513E-01			
		.247E 01	.536E 00			
		-----	-----			
		.223E 02	.434E 01			

TOTAL CROSS SECTION = 22.3 MB ± 5.6 MB (TOTAL ERROR=25 %)

14 N P SPALLATION CROSS SECTION FOR MASS 6 ; E=35.1 MEV

N= 78775 P=4.50CM HG Q=.588E 00 H=24.3CM R=26.3CM B=.076CM

LAB ANGLE	DIFF. CROSS SECT.	CONTRIB. TO TOTAL CROSS SECT.	ASSIGNED ERROR	YIELD	LOW E CORR.	MONITOR COUNTS
15.0	.813E 01	.345E 01	.185E 00	6514	763	78775
30.0	.696E 01	.571E 01	.556E 00	1835	434	55436
45.0	.482E 01	.559E 01	.565E 00	1153	283	71679
60.0	.300E 01	.427E 01	.359E 00	988	188	115309
75.0	.203E 01	.321E 01	.364E 00	594	165	122957
90.0	.149E 01	.245E 01	.419E 00	335	168	114468
105.0	.903E 00	.143E 01	.232E 00	208	94	109794
120.0	.106E 01	.151E 01	.271E 00	119	62	50231
FOR BACK		.437E 00	.234E-01			
		.130E 01	.235E 00			
		-----	-----			
		.294E 02	.321E 01			

TOTAL CROSS SECTION = 29.4 MB ± 3.9 MB (TOTAL ERROR=13 %)

Table 8. (continued)

14 N P SPALLATION CROSS SECTION FOR MASS 7 ; E=35.1 MEV

N= 78775 P=4.50CM HG Q=.588E 00 H=24.3CM R=26.3CM B=.076CM

LAB ANGLE	DIFF. CROSS SECT.	CONTRIB. TO TOTAL CROSS SECT.	ASSIGNED ERROR	YIELD	LOW E CERR.	MONITOR COUNTS
15.0	.265E 01	.112E 01	.120E 00	1875	498	78775
30.0	.172E 01	.141E 01	.987E-01	495	65	55436
45.0	.181E 01	.210E 01	.231E 00	427	112	71679
60.0	.170E 01	.242E 01	.299E 00	508	159	115309
75.0	.124E 01	.196E 01	.231E 00	360	103	122957
90.0	.125E 01	.205E 01	.440E 00	243	178	114468
105.0	.924E 00	.146E 01	.253E 00	206	103	109794
120.0	.545E 00	.774E 00	.198E 00	47	46	50231
FOR		.142E 00	.152E-01			
BACK		.670E 00	.171E 00			
		-----	-----			
		.141E 02	.206E 01			

TOTAL CROSS SECTION = 14.1 MB ± 2.4 MB (TOTAL ERROR=17 %)

14 N P SPALLATION CROSS SECTION FOR MASS 10 ; E=35.1 MEV

N= 78775 P=4.50CM HG Q=.588E 00 H=24.3CM R=26.3CM B=.076CM

LAB ANGLE	DIFF. CROSS SECT.	CONTRIB. TO TOTAL CROSS SECT.	ASSIGNED ERROR	YIELD	LOW E CERR.	MONITOR COUNTS
15.0	.144E 02	.614E 01	.390E 00	11306	1632	78775
30.0	.127E 02	.104E 02	.138E 01	3038	1090	55436
45.0	.948E 01	.110E 02	.198E 01	1813	1013	71679
60.0	.528E 01	.749E 01	.891E 00	1581	485	115309
75.0	.274E 01	.434E 01	.610E 00	742	283	122957
90.0	.195E 01	.320E 01	.784E 00	337	320	114468
105.0	.239E 01	.379E 01	.104E 01	363	436	109794
120.0	.826E 00	.117E 01	.395E 00	47	94	50231
FOR		.777E 00	.494E-01			
BACK		.102E 01	.341E 00			
		-----	-----			
		.493E 02	.785E 01			

TOTAL CROSS SECTION = 49.3 MB ± 8.5 MB (TOTAL ERROR=17 %)

Table 8. (continued)

14 N P SPALLATION CROSS SECTION FOR MASS 11 ; E=35.1 MEV

N= 78775 P=4.50CM HG Q=.588E 00 H=24.3CM R=26.3CM B=.076CM

LAB ANGLE	DIFF. CROSS SECT.	CONTRIB. TO TOTAL CROSS SECT.	ASSIGNED ERROR	YIELD	LOW E CORR.	MONITOR COUNTS
15.0	.612E 01	.260E 01	.322E 00	4124	1353	78775
30.0	.465E 01	.381E 01	.589E 00	1052	464	55436
45.0	.329E 01	.381E 01	.676E 00	636	344	71679
60.0	.233E 01	.331E 01	.868E 00	436	477	115309
75.0	.143E 01	.227E 01	.482E 00	312	225	122957
90.0	.737E 00	.121E 01	.931E-01	222	26	114468
105.0	.314E 00	.498E 00	.723E-01	79	26	109794
120.0	.131E 01	.186E 01	.555E 00	92	132	50231
FOR		.329E 00	.408E-01			
BACK		.323E 01	.960E 00			
		-----	-----			
		.229E 02	.466E 01			

TOTAL CROSS SECTION = 22.9 MB ± 6.3 MB (TOTAL ERROR=28 %)

14 N P SPALLATION CROSS SECTION FOR MASS 6 ; E=37.9 MEV

N= 126329 P=2.11CM HG Q=.274E 01 H=24.2CM R=24.8CM B=.108CM

LAB ANGLE	DIFF. CROSS SECT.	CONTRIB. TO TOTAL CROSS SECT.	ASSIGNED ERROR	YIELD	LOW E CORR.	MONITOR COUNTS
15.0	.851E 01	.361E 01	.263E 00	2885	478	18191
30.0	.575E 01	.471E 01	.345E 00	1206	193	20822
45.0	.454E 01	.627E 01	.530E 00	707	132	22031
65.0	.302E 01	.598E 01	.569E 00	389	81	23491
85.0	.261E 01	.568E 01	.882E 00	234	99	21020
105.0	.186E 01	.393E 01	.727E 00	157	87	20774
FOR		.458E 00	.333E-01			
BACK		.338E 01	.625E 00			
		-----	-----			
		.340E 02	.397E 01			

TOTAL CROSS SECTION = 34.0 MB ± 5.8 MB (TOTAL ERROR=17 %)

Table 8. (continued)

14 N P SPALLATION CROSS SECTION FOR MASS 7 ; E=37.9 MEV

N= 126329 P=2.11CM HG Q=.274E 01 H=24.2CM R=24.8CM B=.108CM

LAB ANGLE	DIFF. CROSS SECT.	CONTRIB. TO TOTAL CROSS SECT.	ASSIGNED ERROR	YIELD	LOW E CORR.	MONITOR COUNTS
15.0	.377E 01	.160E 01	.157E 00	1203	285	18191
30.0	.283E 01	.232E 01	.272E 00	533	155	20822
45.0	.220E 01	.304E 01	.381E 00	311	96	22031
65.0	.238E 01	.471E 01	.855E 00	239	131	23491
85.0	.211E 01	.459E 01	.848E 00	173	96	21020
105.0	.115E 01	.242E 01	.367E 00	109	41	20774
FOR		.202E 00	.199E-01			
BACK		.208E 01	.316E 00			
		-----	-----			
		.210E 02	.322E 01			

TOTAL CROSS SECTION = 21.0 MB ± 4.3 MB (TOTAL ERROR=21 %)

14 N P SPALLATION CROSS SECTION FOR MASS 10 ; E=37.9 MEV

N= 126329 P=2.11CM HG Q=.274E 01 H=24.2CM R=24.8CM B=.108CM

LAB ANGLE	DIFF. CROSS SECT.	CONTRIB. TO TOTAL CROSS SECT.	ASSIGNED ERROR	YIELD	LOW E CORR.	MONITOR COUNTS
15.0	.125E 02	.530E 01	.691E 00	3649	1281	18191
30.0	.980E 01	.804E 01	.102E 01	1787	598	20822
45.0	.717E 01	.990E 01	.127E 01	992	333	22031
65.0	.466E 01	.922E 01	.134E 01	518	206	23491
85.0	.268E 01	.583E 01	.980E 00	231	111	21020
105.0	.118E 01	.250E 01	.434E 00	105	50	20774
FOR		.671E 00	.875E-01			
BACK		.215E 01	.373E 00			
		-----	-----			
		.436E 02	.619E 01			

TOTAL CROSS SECTION = 43.6 MB ± 7.4 MB (TOTAL ERROR=17 %)

Table 8. (continued)

14 N P SPALLATION CROSS SECTION FOR MASS 11 ; E=37.9 MEV

N= 126329 P=2.11CM HG Q=.274E 01 H=24.2CM R=24.8CM B=.108CM

LAB ANGLE	DIFF. CROSS SECT.	CONTRIB. TO TOTAL CROSS SECT.	ASSIGNED ERROR	YIELD	LOW E CORR.	MONITOR COUNTS
15.0	.902E 01	.383E 01	.581E 00	2487	1077	18191
30.0	.678E 01	.556E 01	.103E 01	1044	606	20822
45.0	.378E 01	.522E 01	.929E 00	453	245	22031
65.0	.248E 01	.490E 01	.113E 01	210	175	23491
85.0	.737E 00	.160E 01	.212E 00	75	19	21020
105.0	.810E 00	.171E 01	.184E 00	92	14	20774
FOR		.485E 00	.736E-01			
BACK		.294E 01	.316E 00			
		-----	-----			
		.262E 02	.445E 01			

TOTAL CROSS SECTION = 26.2 MB ± 6.0 MB (TOTAL ERROR=23 %)

VAC P SPALLATION CROSS SECTION FOR MASS 6 ; E=37.9 MEV

N= 10000 P=2.11CM HG Q=.300E 00 H=24.2CM R=24.8CM B=.108CM

LAB ANGLE	DIFF. CROSS SECT.	CONTRIB. TO TOTAL CROSS SECT.	ASSIGNED ERROR	YIELD	LOW E CORR.	MONITOR COUNTS
15.0	.295E 01	.125E 01	.549E-01	2038	172	25004
30.0	.114E 01	.933E 00	.612E-01	414	45	25006
45.0	.973E 00	.113E 01	.144E 00	258	80	30003
60.0	.102E 01	.144E 01	.930E-01	330	29	37027
FOR		.158E 00	.696E-02			
BACK		.442E 01	.284E 00			
		-----	-----			
		.933E 01	.644E 00			

TOTAL CROSS SECTION = 9.3 MB ± 2.9 MB (TOTAL ERROR=31 %)

Table 8. (continued)

VAC P SPALLATION CROSS SECTION FOR MASS 7 ; E=37.9 MEV

N= 10000 P=2.11CM HG Q=.300E 00 H=24.2CM R=24.8CM B=.108CM

LAB ANGLE	DIFF. CROSS SECT.	CONTRIB. TO TOTAL CROSS SECT.	ASSIGNED ERROR	YIELD	LOW E CERR.	MONITOR COUNTS
15.0	.189E 01	.802E 00	.349E-01	1316	100	25004
30.0	.994E 00	.815E 00	.968E-01	312	89	25006
45.0	.774E 00	.898E 00	.129E 00	197	72	30003
60.0	.725E 00	.103E 01	.855E-01	224	32	37027
FOR		.102E 00	.442E-02			
BACK		.315E 01	.262E 00			
		-----	-----			
		.679E 01	.612E 00			

TOTAL CROSS SECTION = 6.8 MB ± 2.2 MB (TOTAL ERROR=32 %)

VAC P SPALLATION CROSS SECTION FOR MASS 10 ; E=37.9 MEV

N= 10000 P=2.11CM HG Q=.300E 00 H=24.2CM R=24.8CM B=.108CM

LAB ANGLE	DIFF. CROSS SECT.	CONTRIB. TO TOTAL CROSS SECT.	ASSIGNED ERROR	YIELD	LOW E CERR.	MONITOR COUNTS
15.0	.102E 01	.431E 00	.639E-01	540	221	25004
30.0	.421E 00	.345E 00	.257E-01	162	8	25006
45.0	.553E 00	.641E 00	.459E-01	183	9	30003
60.0	.371E 00	.527E 00	.443E-01	131	0	37027
FOR		.546E-01	.809E-02			
BACK		.161E 01	.135E 00			
		-----	-----			
		.361E 01	.323E 00			

TOTAL CROSS SECTION = 3.6 MB ± 1.1 MB (TOTAL ERROR=32 %)

Table 8. (continued)

VAC P SPALLATION CROSS SECTION FOR MASS 11 ; E=37.9 MEV

N= 10000 P=2.11CM HG Q=.300E 00 H=24.2CM R=24.8CM B=.108CM

LAB ANGLE	DIFF. CROSS SECT.	CONTRIB. TO TOTAL CROSS SECT.	ASSIGNED ERROR	YIELD	LOW E CORR.	MONITOR COUNTS
15.0	.590E 00	.250E 00	.117E-01	431	11	25004
30.0	.396E 00	.325E 00	.295E-01	141	19	25006
45.0	.357E 00	.414E 00	.449E-01	106	18	30003
60.0	.430E 00	.611E 00	.828E-01	116	36	37027
FOR		.317E-01	.149E-02			
BACK		.187E 01	.253E 00			
		-----	-----			
		.350E 01	.424E 00			

TOTAL CROSS SECTION = 3.5 MB ± 1.4 MB (TOTAL ERROR=39 %)

14 N P SPALLATION CROSS SECTION FOR MASS 6 ; E=40.0 MEV

N= 80353 P=1.37CM HG Q=.284E 01 H=26.1CM R=27.2CM B=.076CM

LAB ANGLE	DIFF. CROSS SECT.	CONTRIB. TO TOTAL CROSS SECT.	ASSIGNED ERROR	YIELD	LOW E CORR.	MONITOR COUNTS
15.0	.486E 01	.206E 01	.191E 00	1600	352	29916
30.0	.435E 01	.356E 01	.387E 00	1099	296	44452
45.0	.339E 01	.394E 01	.448E 00	911	260	66624
60.0	.249E 01	.354E 01	.418E 00	886	266	108429
75.0	.155E 01	.245E 01	.351E 00	534	208	124779
90.0	.103E 01	.168E 01	.283E 00	305	149	118344
105.0	.827E 00	.131E 01	.277E 00	232	165	123380
120.0	.607E 00	.727E 00	.140E 00	233	141	141192
130.0	.884E 00	.742E 00	.142E 00	106	61	37085
FOR		.261E 00	.242E-01			
BACK		.163E 01	.313E 00			
		-----	-----			
		.219E 02	.298E 01			

TOTAL CROSS SECTION = 21.9 MB ± 3.8 MB (TOTAL ERROR=18 %)

Table 8. (continued)

14 N P SPALLATION CROSS SECTION FOR MASS 7 ; E=40.0 MEV

N= 80353 P=1.37CM HG Q=.284E 01 H=26.1CM R=27.2CM B=.076CM

LAB ANGLE	DIFF. CROSS SECT.	CONTRIB. TO TOTAL CROSS SECT.	ASSIGNED ERROR	YIELD	LOW E CORR.	MONITOR COUNTS
15.0	.223E 01	.947E 00	.111E 00	691	204	29916
30.0	.147E 01	.121E 01	.106E 00	398	74	44452
45.0	.159E 01	.185E 01	.224E 00	422	127	66624
60.0	.107E 01	.152E 01	.174E 00	389	107	108429
75.0	.952E 00	.151E 01	.211E 00	334	123	124779
90.0	.832E 00	.136E 01	.203E 00	263	105	118344
105.0	.521E 00	.825E 00	.122E 00	181	69	123380
120.0	.602E 00	.722E 00	.126E 00	245	126	141192
130.0	.635E 00	.533E 00	.954E-01	81	39	37085
FOR		.120E 00	.141E-01			
BACK		.117E 01	.209E 00			
		-----	-----			
		.118E 02	.160E 01			

TOTAL CROSS SECTION = 11.8 MB ± 2.2 MB (TOTAL ERROR=19 %)

14 N P SPALLATION CROSS SECTION FOR MASS 10 ; E=40.0 MEV

N= 80353 P=1.37CM HG Q=.284E 01 H=26.1CM R=27.2CM B=.076CM

LAB ANGLE	DIFF. CROSS SECT.	CONTRIB. TO TOTAL CROSS SECT.	ASSIGNED ERROR	YIELD	LOW E CORR.	MONITOR COUNTS
15.0	.788E 01	.334E 01	.485E 00	2250	912	29916
30.0	.752E 01	.616E 01	.888E 00	1722	690	44452
45.0	.559E 01	.649E 01	.939E 00	1376	554	66624
60.0	.394E 01	.560E 01	.978E 00	1191	633	108429
75.0	.216E 01	.343E 01	.707E 00	613	426	124779
90.0	.138E 01	.226E 01	.479E 00	354	256	118344
105.0	.969E 00	.153E 01	.349E 00	256	209	123380
120.0	.866E 00	.104E 01	.292E 00	235	299	141192
130.0	.693E 00	.582E 00	.169E 00	56	75	37085
FOR		.423E 00	.614E-01			
BACK		.638E 00	.186E 00			
		-----	-----			
		.315E 02	.553E 01			

TOTAL CROSS SECTION = 31.5 MB ± 5.9 MB (TOTAL ERROR=19 %)

Table 8. (continued)

14 N P SPALLATION CROSS SECTION FOR MASS 11 ; E=40.0 MEV

N= 80353 P=1.37CM HG Q=.284E 01 H=26.1CM R=27.2CM B=.076CM

LAB ANGLE	DIFF. CROSS SECT.	CONTRIB. TO TOTAL CROSS SECT.	ASSIGNED ERROR	YIELD	LOW E CORR.	MONITOR COUNTS
15.0	.106E 02	.452E 01	.102E 01	2351	1924	29916
30.0	.696E 01	.571E 01	.127E 01	1243	992	44452
45.0	.327E 01	.379E 01	.774E 00	669	458	66624
60.0	.152E 01	.215E 01	.516E 00	367	334	108429
75.0	.107E 01	.170E 01	.494E 00	216	298	124779
90.0	.509E 00	.834E 00	.823E-01	189	36	118344
105.0	.542E 00	.858E 00	.806E-01	220	40	123380
120.0	.563E 00	.675E 00	.474E-01	312	35	141192
130.0	.789E 00	.662E 00	.707E-01	126	23	37085
FOR BACK		.572E 00 .145E 01	.129E 00 .155E 00			
		----- .229E 02	----- .464E 01			

TOTAL CROSS SECTION = 22.9 MB ± 5.5 MB (TOTAL ERROR=24 %)

14 N P SPALLATION CROSS SECTION FOR MASS 6 ; E=41.9 MEV

N= 81252 P=2.16CM HG Q=.260E 01 H=24.4CM R=24.7CM B=.108CM

LAB ANGLE	DIFF. CROSS SECT.	CONTRIB. TO TOTAL CROSS SECT.	ASSIGNED ERROR	YIELD	LOW E CORR.	MONITOR COUNTS
15.0	.606E 01	.257E 01	.145E 00	5663	699	32758
30.0	.523E 01	.429E 01	.393E 00	2550	561	34451
45.0	.391E 01	.540E 01	.541E 00	1260	306	32341
65.0	.232E 01	.521E 01	.416E 00	557	93	28185
90.0	.155E 01	.380E 01	.441E 00	252	68	22688
110.0	.108E 01	.221E 01	.395E 00	212	113	30979
FOR BACK		.326E 00 .169E 01	.183E-01 .303E 00			
		----- .255E 02	----- .265E 01			

TOTAL CROSS SECTION = 25.5 MB ± 3.6 MB (TOTAL ERROR=14 %)

Table 8. (continued)

14 N P SPALLATION CROSS SECTION FOR MASS 7 ; E=41.9 MEV

N= 81252 P=2.16CM HG Q=.260E 01 H=24.4CM R=24.7CM B=.108CM

LAB ANGLE	DIFF. CROSS SECT.	CONTRIB. TO TOTAL CROSS SECT.	ASSIGNED ERROR	YIELD	LOW E CORR.	MONITOR COUNTS
15.0	.303E 01	.129E 01	.932E-01	2736	449	32758
30.0	.260E 01	.213E 01	.209E 00	1251	295	34451
45.0	.224E 01	.309E 01	.380E 00	681	214	32341
65.0	.154E 01	.346E 01	.362E 00	349	83	28185
90.0	.125E 01	.305E 01	.399E 00	196	61	22688
110.0	.831E 00	.170E 01	.273E 00	175	76	30979
FOR		.163E 00	.118E-01			
BACK		.131E 01	.209E 00			
		-----	-----			
		.162E 02	.194E 01			

TOTAL CROSS SECTION = 16.2 MB ± 2.6 MB (TOTAL ERROR=16 %)

14 N P SPALLATION CROSS SECTION FOR MASS 10 ; E=41.9 MEV

N= 81252 P=2.16CM HG Q=.260E 01 H=24.4CM R=24.7CM B=.108CM

LAB ANGLE	DIFF. CROSS SECT.	CONTRIB. TO TOTAL CROSS SECT.	ASSIGNED ERROR	YIELD	LOW E CORR.	MONITOR COUNTS
15.0	.885E 01	.376E 01	.431E 00	7167	2123	32758
30.0	.717E 01	.588E 01	.421E 00	3661	598	34451
45.0	.554E 01	.765E 01	.104E 01	1618	600	32341
65.0	.321E 01	.720E 01	.839E 00	696	203	28185
90.0	.140E 01	.343E 01	.560E 00	199	90	22688
110.0	.804E 00	.165E 01	.253E 00	173	70	30979
FOR		.476E 00	.545E-01			
BACK		.126E 01	.194E 00			
		-----	-----			
		.313E 02	.380E 01			

TOTAL CROSS SECTION = 31.3 MB ± 4.5 MB (TOTAL ERROR=14 %)

Table 8. (continued)

14 N P SPALLATION CROSS SECTION FOR MASS 11 ; E=41.9 MEV

N= 81252 P=2.16CM HG Q=.260E 01 H=24.4CM R=24.7CM B=.108CM

LAB ANGLE	DIFF. CROSS SECT.	CONTRIB. TO TOTAL CROSS SECT.	ASSIGNED ERROR	YIELD	LOW E CORR.	MONITOR COUNTS
15.0	.973E 01	.413E 01	.452E 00	7984	2229	32758
30.0	.649E 01	.532E 01	.743E 00	2787	1072	34451
45.0	.417E 01	.575E 01	.100E 01	1090	578	32341
65.0	.155E 01	.348E 01	.716E 00	259	176	28185
90.0	.606E 00	.148E 01	.168E 00	105	20	22688
110.0	.642E 00	.132E 01	.109E 00	175	19	30979
FOR		.523E 00	.572E 01			
BACK		.202E 01	.167E 00			
		-----	-----			
		.240E 02	.342E 01			

TOTAL CROSS SECTION = 24.0 MB ± 4.5 MB (TOTAL ERROR=19 %)

14 N P SPALLATION CROSS SECTION FOR MASS 9 ; E=25.8 MEV

N= 760607 P=4.27CM HG Q=.503E 01 H=26.9CM R=27.5CM B=.075CM

LAB ANGLE	DIFF. CROSS SECT.	CONTRIB. TO TOTAL CROSS SECT.	ASSIGNED ERROR	YIELD	LOW E CORR.	MONITOR COUNTS
15.0	.988E 00	.420E 00	.101E 00	119	107	30315
30.0	.740E 00	.607E 00	.181E 00	75	108	60967
45.0	.629E 00	.729E 00	.262E 00	31	77	59020
60.0	.132E 00	.187E 00	.638E 01	14	28	133142
75.0	.278E 01	.441E 01	.120E 01	11	0	182690
90.0	.246E 01	.471E 01	.157E 01	9	0	174110
110.0	.591E 02	.121E 01	.606E 02	2	0	150363
FOR		.531E 01	.128E 01			
BACK		.928E 02	.464E 02			
		-----	-----			
		.211E 01	.659E 00			

TOTAL CROSS SECTION = 2.1 MB ± .7 MB (TOTAL ERROR=32 %)

Table 8. (continued)

14 N P SPALLATION CROSS SECTION FOR MASS 9 ; E=28.6 MEV

N=1026222 P=4.11CM HG Q=.748E 01 H=26.2CM R=27.6CM B=.076CM

LAB ANGLE	DIFF. CROSS SECT.	CONTRIB. TO TOTAL CROSS SECT.	ASSIGNED ERROR	YIELD	LOW E CERR.	MONITOR COUNTS
20.0	.235E 01	.901E 00	.123E 00	399	143	32621
25.0	.223E 01	.516E 00	.746E-01	358	139	39030
30.0	.191E 01	.112E 01	.195E 00	366	189	62753
45.0	.134E 01	.155E 01	.376E 00	237	219	103480
60.0	.597E 00	.848E 00	.183E 00	123	89	132042
75.0	.416E 00	.660E 00	.234E 00	50	119	168217
90.0	.227E 00	.372E 00	.100E 00	56	62	223078
105.0	.763E-01	.121E 00	.391E-01	16	26	228391
120.0	.124E 00	.176E 00	.615E-01	18	39	171014
FOR		.225E 00	.307E-01			
BACK		.152E 00	.532E-01			
		-----	-----			
		.665E 01	.147E 01			

TOTAL CROSS SECTION = 6.6 MB ± 1.6 MB (TOTAL ERROR=24 %)

14 N P SPALLATION CROSS SECTION FOR MASS 9 ; E=31.9 MEV

N= 15704 P=5.36CM HG Q=.100E 00 H=25.7CM R=26.3CM B=.076CM

LAB ANGLE	DIFF. CROSS SECT.	CONTRIB. TO TOTAL CROSS SECT.	ASSIGNED ERROR	YIELD	LOW E CERR.	MONITOR COUNTS
15.0	.291E 01	.124E 01	.100E 00	822	147	28419
30.0	.184E 01	.151E 01	.108E 00	351	44	35519
45.0	.109E 01	.126E 01	.657E-01	622	51	73288
60.0	.809E 00	.115E 01	.152E 00	145	44	71363
75.0	.296E 00	.470E 00	.892E-01	48	25	83930
90.0	.240E 00	.394E 00	.102E 00	37	36	107217
105.0	.206E 00	.327E 00	.111E 00	22	44	108880
120.0	.864E-01	.123E 00	.305E-01	17	12	102567
FOR		.157E 00	.127E-01			
BACK		.106E 00	.264E-01			
		-----	-----			
		.673E 01	.799E 00			

TOTAL CROSS SECTION = 6.7 MB ± .9 MB (TOTAL ERROR=13 %)

Table 8. (continued)

14 N P SPALLATION CROSS SECTION FOR MASS 9 ; E=35.1 MEV

N= 78775 P=4.50CM HG Q=.588E 00 H=24.3CM R=26.3CM B=.076CM

LAB ANGLE	DIFF. CROSS SECT.	CONTRIB. TO TOTAL CROSS SECT.	ASSIGNED ERROR	YIELD	LOW E CORR.	MONITOR COUNTS
15.0	.368E 01	.156E 01	.169E 00	2589	708	78775
30.0	.317E 01	.260E 01	.415E 00	707	326	55436
45.0	.203E 01	.235E 01	.368E 00	420	185	71679
60.0	.117E 01	.166E 01	.360E 00	263	196	115309
75.0	.975E 00	.155E 01	.462E 00	148	217	122957
90.0	.493E 00	.809E 00	.242E 00	68	98	114468
105.0	.272E 00	.431E 00	.131E 00	37	54	109794
120.0	.117E 01	.166E 01	.833E 02	2	0	50231
FOR		.198E 00	.215E 01			
BACK		.144E 01	.720E 02			
		-----	-----			
		.112E 02	.218E 01			

TOTAL CROSS SECTION = 11.2 MB ± 2.2 MB (TOTAL ERROR=20 %)

14 N P SPALLATION CROSS SECTION FOR MASS 9 ; E=37.9 MEV

N= 126329 P=2.11CM HG Q=.274E 01 H=24.2CM R=24.8CM B=.108CM

LAB ANGLE	DIFF. CROSS SECT.	CONTRIB. TO TOTAL CROSS SECT.	ASSIGNED ERROR	YIELD	LOW E CORR.	MONITOR COUNTS
15.0	.403E 01	.171E 01	.225E 00	1178	413	18191
30.0	.243E 01	.199E 01	.200E 00	480	111	20822
45.0	.175E 01	.241E 01	.305E 00	247	76	22031
65.0	.121E 01	.239E 01	.443E 00	122	66	23491
85.0	.635E 00	.138E 01	.237E 00	57	24	21020
105.0	.344E 00	.725E 00	.166E 00	27	18	20774
FOR		.216E 00	.285E 01			
BACK		.624E 00	.143E 00			
		-----	-----			
		.115E 02	.175E 01			

TOTAL CROSS SECTION = 11.5 MB ± 2.1 MB (TOTAL ERROR=18 %)

Table 8. (continued)

VAC P SPALLATION CROSS SECTION FOR MASS 9 ; E=37.9 MEV

N= 10000 P=2.11CM HG Q=.300E 00 H=24.2CM R=24.8CM B=.108CM

LAB ANGLE	DIFF. CROSS SECT.	CONTRIB. TO TOTAL CROSS SECT.	ASSIGNED ERROR	YIELD	LOW E CORR.	MONITOR COUNTS
15.0	.843E 00	.358E 00	.362E-01	512	120	25004
30.0	.394E 00	.323E 00	.260E-01	150	9	25006
45.0	.492E 00	.571E 00	.417E-01	164	7	30003
60.0	.292E 00	.414E 00	.402E-01	103	0	37027
FOR BACK		.453E-01 .127E 01	.458E-02 .123E 00			
		----- .298E 01	----- .272E 00			

TOTAL CROSS SECTION = 3.0 MB ± .9 MB (TOTAL ERROR=31 %)

14 N P SPALLATION CROSS SECTION FOR MASS 9 ; E=40.0 MEV

N= 80353 P=1.37CM HG Q=.284E 01 H=26.1CM R=27.2CM B=.076CM

LAB ANGLE	DIFF. CROSS SECT.	CONTRIB. TO TOTAL CROSS SECT.	ASSIGNED ERROR	YIELD	LOW E CORR.	MONITOR COUNTS
15.0	.268E 01	.114E 01	.188E 00	725	351	29916
30.0	.210E 01	.172E 01	.267E 00	468	205	44452
45.0	.172E 01	.199E 01	.342E 00	392	200	66624
60.0	.962E 00	.137E 01	.275E 00	269	176	108429
75.0	.458E 00	.726E 00	.143E 00	136	84	124779
90.0	.362E 00	.593E 00	.145E 00	84	76	118344
105.0	.340E 00	.538E 00	.161E 00	67	96	123380
120.0	.177E 00	.212E 00	.419E-01	69	40	141192
130.0	.349E 00	.293E 00	.787E-01	32	34	37085
FOR BACK		.144E 00 .643E 00	.238E-01 .173E 00			
		----- .936E 01	----- .184E 01			

TOTAL CROSS SECTION = 9.4 MB ± 2.2 MB (TOTAL ERROR=23 %)

Table 8. (continued)

14 N P SPALLATION CROSS SECTION FOR MASS 9 ; E=41.9 MEV

N= 81252 P=2.16CM HG Q=.260E 01 H=24.4CM R=24.7CM B=.108CM

LAB ANGLE	DIFF. CROSS SECT.	CONTRIB. TO TOTAL CROSS SECT.	ASSIGNED ERROR	YIELD	LOW E CERR.	MONITOR COUNTS
15.0	.321E 01	.136E 01	.140E 00	2687	686	32758
30.0	.248E 01	.203E 01	.209E 00	1178	295	34451
45.0	.156E 01	.216E 01	.307E 00	453	173	32341
65.0	.127E 01	.285E 01	.591E 00	211	145	28185
90.0	.528E 00	.130E 01	.278E 00	65	44	22688
110.0	.298E 00	.611E 00	.951E-01	67	23	30979
FOR		.173E 00	.178E-01			
BACK		.468E 00	.728E-01			
		-----	-----			
		.110E 02	.171E 01			

TOTAL CROSS SECTION = 11.0 MB \pm 2.0 MB (TOTAL ERROR=18 %)

VAC P SPALLATION CROSS SECTION FOR MASS 9 ; E=41.9 MEV

N= 242535 P=2.16CM HG Q=.713E 01 H=24.4CM R=24.7CM B=.108CM

LAB ANGLE	DIFF. CROSS SECT.	CONTRIB. TO TOTAL CROSS SECT.	ASSIGNED ERROR	YIELD	LOW E CERR.	MONITOR COUNTS
15.0	.411E 00	.175E 00	.127E-01	165	0	13384
30.0	.452E 00	.371E 00	.375E-01	115	18	18256
45.0	.750E 00	.869E 00	.148E 00	103	47	17289
60.0	.535E 00	.760E 00	.943E-01	102	24	24702
75.0	.733E 00	.116E 01	.226E 00	69	39	17147
90.0	.593E 00	.973E 00	.144E 00	65	19	16961
FOR		.221E-01	.161E-02			
BACK		.162E 01	.239E 00			
		-----	-----			
		.595E 01	.904E 00			

TOTAL CROSS SECTION = 5.9 MB \pm 1.7 MB (TOTAL ERROR=29 %)

Table 8. (continued)

16 0 P SPALLATION CROSS SECTION FOR MASS 6 ; E=30.0 MEV

N= 27783 P=2.27CM HG Q=.307E 00 H=24.1CM R=24.5CM B=.109CM

LAB ANGLE	DIFF. CROSS SECT.	CONTRIB. TO TOTAL CROSS SECT.	ASSIGNED ERROR	YIELD	LOW E CORR.	MONITOR COUNTS
15.0	.306E 00	.130E 00	.172E-01	52	7	15872
30.0	.257E 00	.211E 00	.270E-01	47	0	27783
45.0	.161E 00	.187E 00	.356E-01	21	0	27613
60.0	.199E 00	.283E 00	.590E-01	18	6	30965
75.0	.499E 00	.791E 00	.128E 00	36	7	24525
FOR BACK		.164E-01 .177E 01	.218E-02 .286E 00			
		----- .339E 01	----- .555E 00			

TOTAL CROSS SECTION = 3.4 MB \pm 1.4 MB (TOTAL ERROR=43 %)

16 0 P SPALLATION CROSS SECTION FOR MASS 11 ; E=30.0 MEV

N= 27783 P=2.27CM HG Q=.307E 00 H=24.1CM R=24.5CM B=.109CM

LAB ANGLE	DIFF. CROSS SECT.	CONTRIB. TO TOTAL CROSS SECT.	ASSIGNED ERROR	YIELD	LOW E CORR.	MONITOR COUNTS
15.0	.133E 01	.565E 00	.760E-01	193	64	15872
30.0	.105E 01	.863E 00	.812E-01	165	27	27783
45.0	.261E 00	.303E 00	.605E-01	23	11	27613
60.0	.332E-01	.472E-01	.236E-01	4	0	30965
75.0	.813E-01	.129E 00	.368E-01	7	0	24525
FOR BACK		.716E-01 .289E 00	.962E-02 .825E-01			
		----- .227E 01	----- .370E 00			

TOTAL CROSS SECTION = 2.3 MB \pm .5 MB (TOTAL ERROR=23 %)

Table 8. (continued)

16 O P SPALLATION CROSS SECTION FOR MASS 6 ; E=33.7 MEV

N= 79459 P=2.14CM HG Q=.141E 01 H=26.6CM R=27.2CM B=.075CM

LAB ANGLE	DIFF. CROSS SECT.	CONTRIB. TO TOTAL CROSS SECT.	ASSIGNED ERROR	YIELD	LOW E CORR.	MONITOR COUNTS
15.0	.401E 00	.170E 00	.203E-01	163	43	48848
30.0	.253E 00	.208E 00	.210E-01	120	20	97606
45.0	.620E 00	.719E 00	.796E-01	89	14	41575
60.0	.473E 00	.672E 00	.918E-01	51	8	37884
75.0	.176E 00	.279E 00	.928E-01	9	0	17240
FOR		.216E-01	.258E-02			
BACK		.624E 00	.208E 00			
		-----	-----			
		.269E 01	.516E 00			

TOTAL CROSS SECTION = 2.7 MB ± .8 MB (TOTAL ERROR=31 %)

16 O P SPALLATION CROSS SECTION FOR MASS 7 ; E=33.7 MEV

N= 79459 P=2.14CM HG Q=.141E 01 H=26.6CM R=27.2CM B=.075CM

LAB ANGLE	DIFF. CROSS SECT.	CONTRIB. TO TOTAL CROSS SECT.	ASSIGNED ERROR	YIELD	LOW E CORR.	MONITOR COUNTS
15.0	.378E 00	.160E 00	.203E-01	151	43	48848
30.0	.210E 00	.172E 00	.205E-01	95	21	97606
45.0	.403E 00	.467E 00	.691E-01	53	14	41575
60.0	.305E 00	.433E 00	.766E-01	29	9	37884
75.0	.976E-01	.155E 00	.619E-01	5	0	17240
FOR		.203E-01	.258E-02			
BACK		.347E 00	.139E 00			
		-----	-----			
		.175E 01	.390E 00			

TOTAL CROSS SECTION = 1.8 MB ± .6 MB (TOTAL ERROR=32 %)

Table 8. (continued)

16 O P SPALLATION CROSS SECTION FOR MASS 10 ; E=33.7 MEV

N= 79459 P=2.14CM HG Q=.141E 01 H=26.6CM R=27.2CM B=.075CM

LAB ANGLE	DIFF. CROSS SECT.	CONTRIB. TO TOTAL CROSS SECT.	ASSIGNED ERROR	YIELD	LOW E CORR.	MONITOR COUNTS
15.0	.790E 00	.336E 00	.371E-01	323	83	48848
30.0	.413E 00	.339E 00	.514E-01	163	65	97606
45.0	.343E 00	.398E 00	.726E-01	40	17	41575
60.0	.281E 00	.399E 00	.117E 00	16	19	37884
75.0	.976E-01	.155E 00	.619E-01	5	0	17240
FOR		.425E-01	.469E-02			
BACK		.347E 00	.139E 00			
		-----	-----			
		.201E 01	.484E 00			

TOTAL CROSS SECTION = 2.0 MB ± .7 MB (TOTAL ERROR=33 %)

16 O P SPALLATION CROSS SECTION FOR MASS 11 ; E=33.7 MEV

N= 79459 P=2.14CM HG Q=.141E 01 H=26.6CM R=27.2CM B=.075CM

LAB ANGLE	DIFF. CROSS SECT.	CONTRIB. TO TOTAL CROSS SECT.	ASSIGNED ERROR	YIELD	LOW E CORR.	MONITOR COUNTS
15.0	.804E 01	.341E 01	.711E 00	2413	1718	48848
30.0	.477E 01	.391E 01	.805E 00	1555	1081	97606
45.0	.356E 01	.412E 01	.104E 01	295	296	41575
60.0	.108E 01	.154E 01	.250E 00	95	40	37884
75.0	.703E 00	.111E 01	.319E 00	17	19	17240
FOR		.432E 00	.900E-01			
BACK		.250E 01	.715E 00			
		-----	-----			
		.170E 02	.393E 01			

TOTAL CROSS SECTION = 17.0 MB ± 5.3 MB (TOTAL ERROR=31 %)

Table 8. (continued)

16 O P SPALLATION CROSS SECTION FOR MASS 6 ; E=37.9 MEV

N= 257351 P=2.06CM HG Q=.508E 01 H=24.2CM R=24.8CM B=.108CM

LAB ANGLE	DIFF. CROSS SECT.	CONTRIB. TO TOTAL CROSS SECT.	ASSIGNED ERROR	YIELD	LOW E CORR.	MONITOR COUNTS
15.0	.101E 01	.428E 00	.997E-01	282	242	26977
30.0	.525E 00	.431E 00	.116E 00	97	110	37997
45.0	.479E 00	.556E 00	.143E 00	81	82	45689
60.0	.468E 00	.665E 00	.175E 00	78	84	56450
75.0	.471E 00	.746E 00	.175E 00	90	76	63796
90.0	.355E 00	.583E 00	.183E 00	39	63	53419
FOR BACK		.542E-01 .971E 00 ----- .443E 01	.126E-01 .305E 00 ----- .121E 01			

TOTAL CROSS SECTION = 4.4 MB ± 1.7 MB (TOTAL ERROR=39 %)

16 O P SPALLATION CROSS SECTION FOR MASS 7 ; E=37.9 MEV

N= 257351 P=2.06CM HG Q=.508E 01 H=24.2CM R=24.8CM B=.108CM

LAB ANGLE	DIFF. CROSS SECT.	CONTRIB. TO TOTAL CROSS SECT.	ASSIGNED ERROR	YIELD	LOW E CORR.	MONITOR COUNTS
15.0	.766E 00	.325E 00	.578E-01	260	138	26977
30.0	.624E 00	.512E 00	.122E 00	131	115	37997
45.0	.682E 00	.791E 00	.253E 00	85	147	45689
60.0	.408E 00	.579E 00	.129E 00	80	61	56450
75.0	.459E 00	.728E 00	.194E 00	77	85	63796
90.0	.265E 00	.434E 00	.123E 00	34	42	53419
FOR BACK		.412E-01 .724E 00 ----- .413E 01	.732E-02 .206E 00 ----- .109E 01			

TOTAL CROSS SECTION = 4.1 MB ± 1.5 MB (TOTAL ERROR=35 %)

Table 8. (continued)

16 O P SPALLATION CROSS SECTION FOR MASS 10 ; E=37.9 MEV

N= 257351 P=2.06CM HG Q=.508E 01 H=24.2CM R=24.8CM B=.108CM

LAB ANGLE	DIFF. CROSS SECT.	CONTRIB. TO TOTAL CROSS SECT.	ASSIGNED ERROR	YIELD	LOW E CORR.	MONITOR COUNTS
15.0	.221E 01	.937E 00	.148E 00	788	359	26977
30.0	.159E 01	.130E 01	.190E 00	448	178	37997
45.0	.429E 00	.498E 00	.165E 00	50	96	45689
60.0	.442E 00	.628E 00	.221E 00	46	107	56450
75.0	.343E 00	.543E 00	.175E 00	44	77	63796
90.0	.282E 00	.463E 00	.143E 00	32	49	53419
FOR		.119E 00	.188E 01			
BACK		.771E 00	.238E 00			
		-----	-----			
		.526E 01	.130E 01			

TOTAL CROSS SECTION = 5.3 MB ± 1.7 MB (TOTAL ERROR=32 %)

16 O P SPALLATION CROSS SECTION FOR MASS 11 ; E=37.9 MEV

N= 257351 P=2.06CM HG Q=.508E 01 H=24.2CM R=24.8CM B=.108CM

LAB ANGLE	DIFF. CROSS SECT.	CONTRIB. TO TOTAL CROSS SECT.	ASSIGNED ERROR	YIELD	LOW E CORR.	MONITOR COUNTS
15.0	.156E 02	.664E 01	.909E 00	5913	2220	26977
30.0	.107E 02	.881E 01	.141E 01	2875	1356	37997
45.0	.655E 01	.759E 01	.144E 01	1385	841	45689
60.0	.336E 01	.478E 01	.100E 01	678	486	56450
75.0	.442E 00	.701E 00	.225E 00	57	99	63796
90.0	.331E 00	.543E 00	.144E 00	46	49	53419
FOR		.841E 00	.115E 00			
BACK		.904E 00	.240E 00			
		-----	-----			
		.308E 02	.549E 01			

TOTAL CROSS SECTION = 30.8 MB ± 6.1 MB (TOTAL ERROR=20 %)

Table 8. (continued)

16 O P SPALLATION CROSS SECTION FOR MASS 6 ; E=41.9 MEV

N= 242535 P=2.16CM HG Q=.713E 01 H=24.4CM R=24.7CM B=.108CM

LAB ANGLE	DIFF. CROSS SECT.	CONTRIB. TO TOTAL CROSS SECT.	ASSIGNED ERROR	YIELD	LOW E CERR.	MONITOR COUNTS
15.0	.222E 01	.942E 00	.134E 00	1599	630	33546
30.0	.182E 01	.149E 01	.201E 00	730	262	33823
45.0	.165E 01	.191E 01	.275E 00	469	183	34187
60.0	.214E 01	.304E 01	.493E 00	721	340	52009
75.0	.151E 01	.239E 01	.424E 00	433	233	51379
90.0	.112E 01	.183E 01	.373E 00	211	140	37591
FOR		.119E 00	.170E 01			
BACK		.305E 01	.621E 00			
		-----	-----			
		.148E 02	.254E 01			

TOTAL CROSS SECTION = 14.8 MB \pm 4.1 MB (TOTAL ERROR=28 %)

16 O P SPALLATION CROSS SECTION FOR MASS 7 ; E=41.9 MEV

N= 242535 P=2.16CM HG Q=.713E 01 H=24.4CM R=24.7CM B=.108CM

LAB ANGLE	DIFF. CROSS SECT.	CONTRIB. TO TOTAL CROSS SECT.	ASSIGNED ERROR	YIELD	LOW E CERR.	MONITOR COUNTS
15.0	.258E 01	.110E 01	.154E 00	1870	726	33546
30.0	.181E 01	.148E 01	.197E 00	729	257	33823
45.0	.168E 01	.195E 01	.263E 00	490	174	34187
60.0	.156E 01	.222E 01	.416E 00	488	287	52009
75.0	.136E 01	.216E 01	.429E 00	366	236	51379
90.0	.117E 01	.191E 01	.381E 00	223	143	37591
FOR		.139E 00	.195E 01			
BACK		.318E 01	.634E 00			
		-----	-----			
		.141E 02	.249E 01			

TOTAL CROSS SECTION = 14.1 MB \pm 4.1 MB (TOTAL ERROR=29 %)

Table 8. (continued)

16 O P SPALLATION CROSS SECTION FOR MASS 10 ; E=41.9 MEV

N= 242535 P=2.16CM HG Q=.713E 01 H=24.4CM R=24.7CM B=.108CM

LAB ANGLE	DIFF. CROSS SECT.	CONTRIB. TO TOTAL CROSS SECT.	ASSIGNED ERROR	YIELD	LOW E CORR.	MONITOR COUNTS
15.0	.429E 01	.182E 01	.427E 00	2293	2020	33546
30.0	.229E 01	.188E 01	.325E 00	818	429	33823
45.0	.151E 01	.175E 01	.270E 00	416	180	34187
60.0	.137E 01	.195E 01	.391E 00	411	270	52009
75.0	.185E 01	.294E 01	.706E 00	427	392	51379
90.0	.685E 00	.112E 01	.242E 00	125	90	37591
FOR		.231E 00	.541E-01			
BACK		.187E 01	.403E 00			
		-----	-----			
		.136E 02	.282E 01			

TOTAL CROSS SECTION = 13.6 MB \pm 3.8 MB (TOTAL ERROR=28 %)

16 O P SPALLATION CROSS SECTION FOR MASS 11 ; E=41.9 MEV

N= 242535 P=2.16CM HG Q=.713E 01 H=24.4CM R=24.7CM B=.108CM

LAB ANGLE	DIFF. CROSS SECT.	CONTRIB. TO TOTAL CROSS SECT.	ASSIGNED ERROR	YIELD	LOW E CORR.	MONITOR COUNTS
15.0	.210E 02	.890E 01	.155E 01	13722	7351	33546
30.0	.124E 02	.102E 02	.162E 01	4639	2153	33823
45.0	.787E 01	.913E 01	.157E 01	2043	1071	34187
60.0	.474E 01	.674E 01	.148E 01	1322	1030	52009
75.0	.289E 01	.457E 01	.125E 01	581	694	51379
90.0	.138E 01	.226E 01	.672E 00	177	256	37591
FOR		.113E 01	.197E 00			
BACK		.377E 01	.112E 01			
		-----	-----			
		.467E 02	.947E 01			

TOTAL CROSS SECTION = 46.7 MB \pm 11.6 MB (TOTAL ERROR=25 %)

Table 8. (continued)

VAC P SPALLATION CROSS SECTION FOR MASS 10 ; E=41.9 MEV						

N= 242535 P=2.16CM HG Q=.713E 01 H=24.4CM R=24.7CM B=.108CM						
LAB ANGLE	DIFF. CROSS SECT.	CONTRIB. TO TOTAL CROSS SECT.	ASSIGNED ERROR	YIELD	LOW E CORR.	MONITOR COUNTS
15.0	.364E 00	.155E 00	.178E-01	119	27	13384
30.0	.350E 00	.287E 00	.385E-01	82	21	18256
45.0	.550E 00	.638E 00	.648E-01	100	10	17289
60.0	.616E 00	.875E 00	.180E 00	88	57	24702
75.0	.814E 00	.129E 01	.262E 00	74	46	17147
90.0	.536E 00	.880E 00	.220E 00	40	36	16961
FOR		.196E-01	.225E-02			
BACK		.147E 01	.366E 00			
		-----	-----			
		.561E 01	.115E 01			

TOTAL CROSS SECTION = 5.6 MB \pm 1.9 MB (TOTAL ERROR=34 %)

VAC P SPALLATION CROSS SECTION FOR MASS 11 ; E=41.9 MEV						

N= 242535 P=2.16CM HG Q=.713E 01 H=24.4CM R=24.7CM B=.108CM						
LAB ANGLE	DIFF. CROSS SECT.	CONTRIB. TO TOTAL CROSS SECT.	ASSIGNED ERROR	YIELD	LOW E CORR.	MONITOR COUNTS
15.0	.232E 00	.985E-01	.953E-02	93	0	13384
30.0	.431E 00	.354E 00	.435E-01	103	24	18256
45.0	.545E 00	.632E 00	.106E 00	76	33	17289
60.0	.607E 00	.863E 00	.143E 00	100	43	24702
75.0	.427E 00	.677E 00	.924E-01	53	10	17147
90.0	.438E 00	.718E 00	.135E 00	42	20	16961
FOR		.125E-01	.121E-02			
BACK		.120E 01	.225E 00			
		-----	-----			
		.455E 01	.756E 00			

TOTAL CROSS SECTION = 4.5 MB \pm 1.4 MB (TOTAL ERROR=30 %)

Table 8. (continued)

VAC P SPALLATION CROSS SECTION FOR MASS 6 ; E=41.9 MEV

N= 242535 P=2.16CM HG Q=.713E 01 H=24.4CM R=24.7CM B=.108CM

LAB ANGLE	DIFF. CROSS SECT.	CONTRIB. TO TOTAL CROSS SECT.	ASSIGNED ERROR	YIELD	LOW E CORR.	MONITOR COUNTS
15.0	.120E 01	.508E 00	.740E-01	345	135	13384
30.0	.103E 01	.847E 00	.168E 00	186	118	18256
45.0	.119E 01	.139E 01	.197E 00	176	63	17289
60.0	.133E 01	.190E 01	.452E 00	166	148	24702
75.0	.977E 00	.155E 01	.336E 00	84	60	17147
90.0	.109E 01	.180E 01	.352E 00	97	58	16961
FOR		.643E-01	.936E-02			
BACK		.299E 01	.585E 00			
		-----	-----			
		.110E 02	.218E 01			

TOTAL CROSS SECTION = 11.0 MB \pm 3.7 MB (TOTAL ERROR=33 %)

VAC P SPALLATION CROSS SECTION FOR MASS 7 ; E=41.9 MEV

N= 242535 P=2.16CM HG Q=.713E 01 H=24.4CM R=24.7CM B=.108CM

LAB ANGLE	DIFF. CROSS SECT.	CONTRIB. TO TOTAL CROSS SECT.	ASSIGNED ERROR	YIELD	LOW E CORR.	MONITOR COUNTS
15.0	.122E 01	.520E 00	.102E 00	301	190	13384
30.0	.104E 01	.852E 00	.198E 00	166	140	18256
45.0	.985E 00	.114E 01	.172E 00	142	55	17289
60.0	.841E 00	.119E 01	.224E 00	127	71	24702
75.0	.807E 00	.128E 01	.247E 00	76	43	17147
90.0	.104E 01	.170E 01	.363E 00	87	60	16961
FOR		.658E-01	.129E-01			
BACK		.283E 01	.604E 00			
		-----	-----			
		.959E 01	.192E 01			

TOTAL CROSS SECTION = 9.6 MB \pm 3.4 MB (TOTAL ERROR=35 %)

Table 9. Summary of Measured Cross-Sections for Proton Spallation of ^{14}N and ^{16}O .

TOTAL CROSS SECTIONS FROM PROTON SPALLATION OF ^{14}N

E (MEV) P	MASS 6		MASS 7		MASS 9		MASS10		MASS11	
17.0	0.0±	0.0	36.6±	14.1	0.0±	0.0	26.4±	11.2	67.9±	16.4
21.7	3.1±	.7	41.2±	7.2	0.0±	0.0	61.1±	13.6	39.5±	10.1
25.8	16.3±	3.7	25.7±	4.2	2.1±	.7	60.5±	12.2	22.8±	5.6
28.6	22.0±	2.2	17.5±	1.8	6.6±	1.6	57.2±	8.2	19.5±	4.6
31.9	23.1±	1.9	14.4±	1.8	6.7±	.9	45.9±	5.2	22.3±	5.6
35.1	29.4±	3.9	14.1±	2.4	11.2±	2.2	49.3±	8.5	22.9±	6.3
37.9	28.8±	5.8	16.9±	4.3	9.5±	2.1	41.4±	7.4	23.8±	6.0
40.0	21.9±	3.8	11.8±	2.2	9.4±	2.2	31.5±	5.9	22.9±	5.5
41.9	17.7±	2.5	9.3±	1.5	6.8±	1.5	27.4±	3.5	20.8±	3.5

TOTAL CROSS SECTIONS FROM PROTON SPALLATION OF 16 O

E (MEV) P	MASS 6	MASS 7	MASS10	MASS11
30.0	1.5± .5	.0+ .0	.0+ .0	2.3± .5
33.7	2.7± .8	1.8± .6	2.0± .7	17.0± 5.3
37.9	4.4± 1.7	4.1± 1.5	5.3± 1.7	30.8± 6.1
41.9	3.8± 1.5	4.5± 1.5	8.0± 2.5	42.2± 10.2

TOTAL CROSS SECTIONS FROM PROTON SPALLATION OF ^{12}C

E_p (MEV)	MASS 6	MASS 7	MASS 8	MASS 9	MASS 10	MASS 11
21.7	.0+ .0	.0+ .0	.0+ .0	.0+ .0	.0+ .0	45.± 7.
24.6	.0+ .0	.0+ .0	.0+ .0	.0+ .0	3.7± .6	64.± 17.
28.0	3.9± .8	3.2± .6	.0+ .0	.0+ .0	7.0± 1.1	96.± 22.
29.5	4.0± .8	8.7± 2.1	.0+ .0	.0+ .0	10.0± 1.8	113.± 20.
32.0	6.3± 1.0	15.2± 3.0	.6± .2	.7± .2	9.7± 1.7	121.± 28.
34.0	8.6± 1.4	23.2± 3.7	.9± .2	1.3± .3	10.2± 1.8	116.± 25.
36.0	7.2± 1.1	24.1± 4.2	1.8± .4	1.7± .4	11.1± 2.1	95.± 21.
39.8	9.9± 1.5	33.1± 5.4	1.9± .5	2.4± .5	16.3± 3.3	91.± 18.
44.0	11.2± 2.2	34.4± 6.6	2.4± .6	2.5± .6	18.4± 4.1	87.± 20.

Table 10. Summary of Cross-Sections for Proton Spallation of ^{12}C (DLA 70).

ANGULAR DISTRIBUTIONS TARGET 14 N

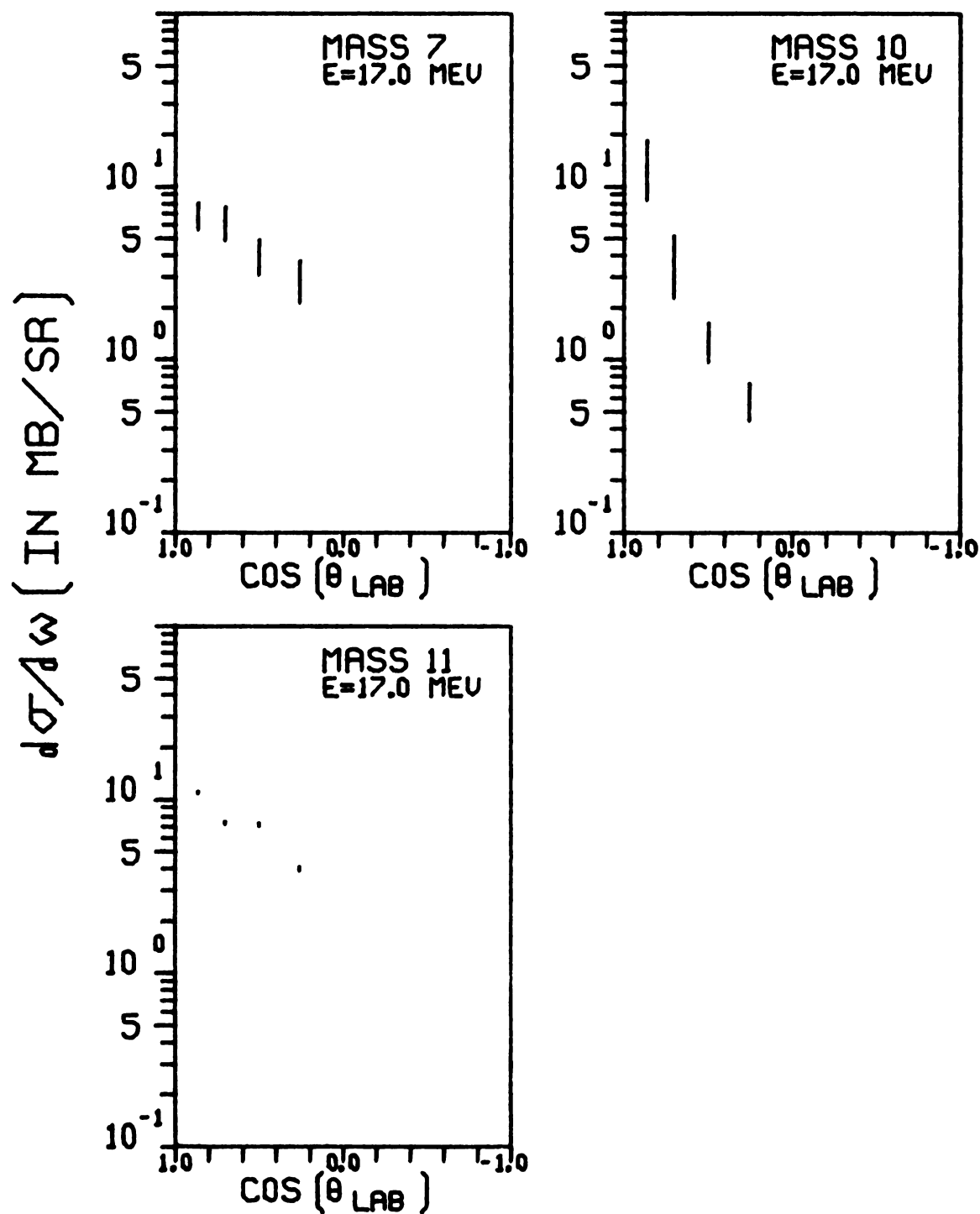


Figure 12. Angular Distribution for Masses 6 to 11
from Proton Spallation of ^{14}N and ^{16}O .

ANGULAR DISTRIBUTIONS TARGET 14 N

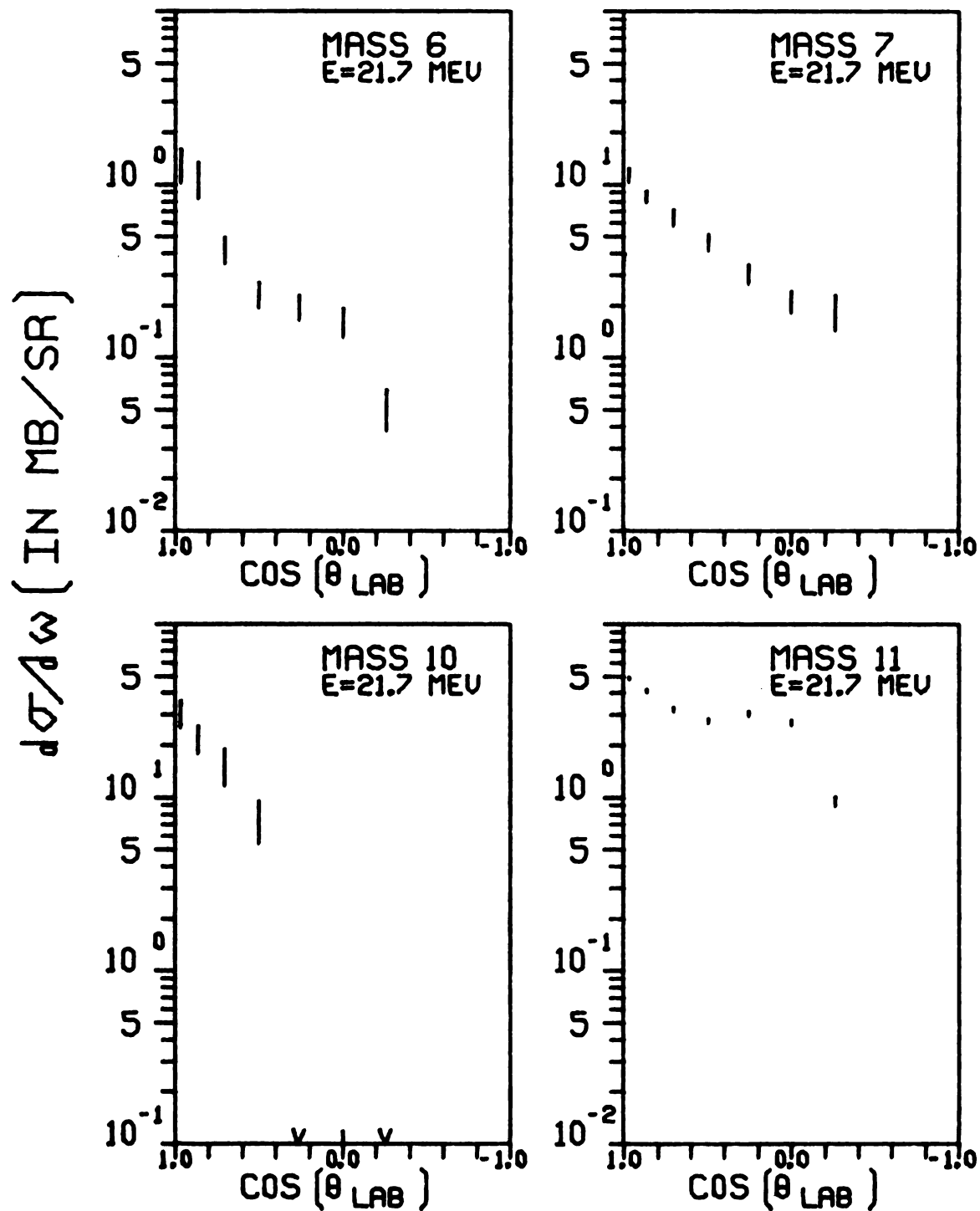


Figure 12. (continued)

ANGULAR DISTRIBUTIONS TARGET 14 N

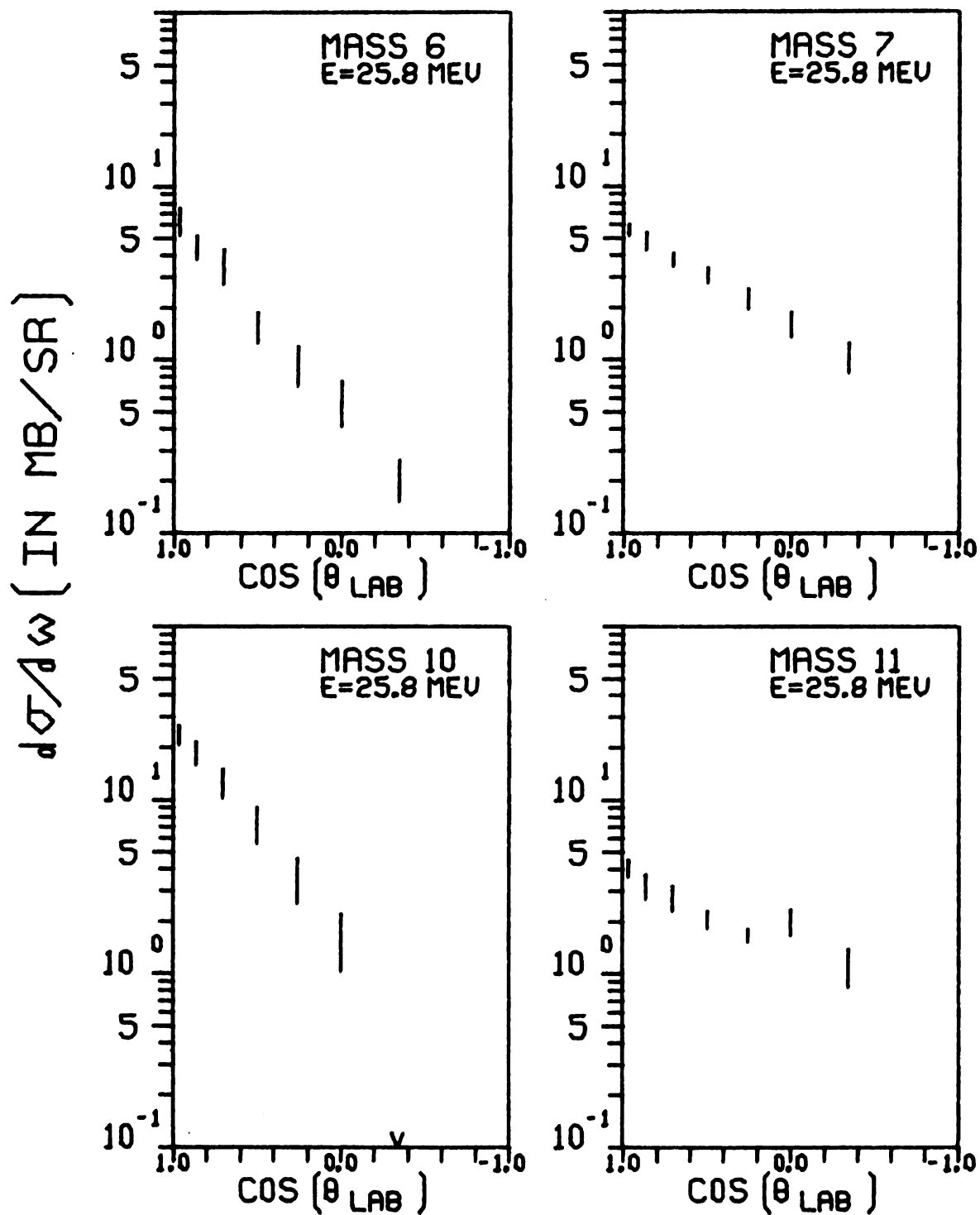


Figure 12. (continued)

ANGULAR DISTRIBUTIONS TARGET 14 N

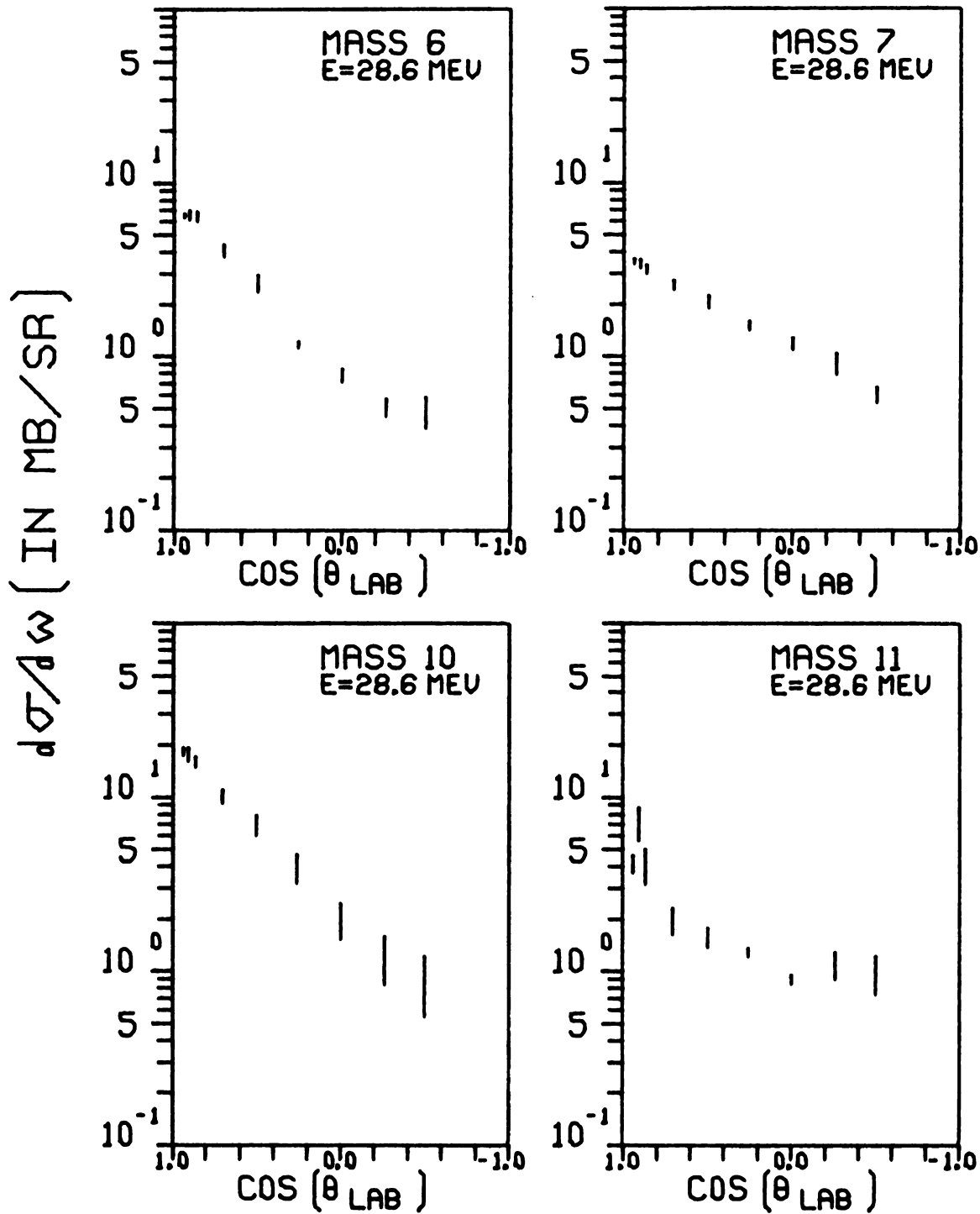


Figure 12. (continued)

ANGULAR DISTRIBUTIONS TARGET 14 N

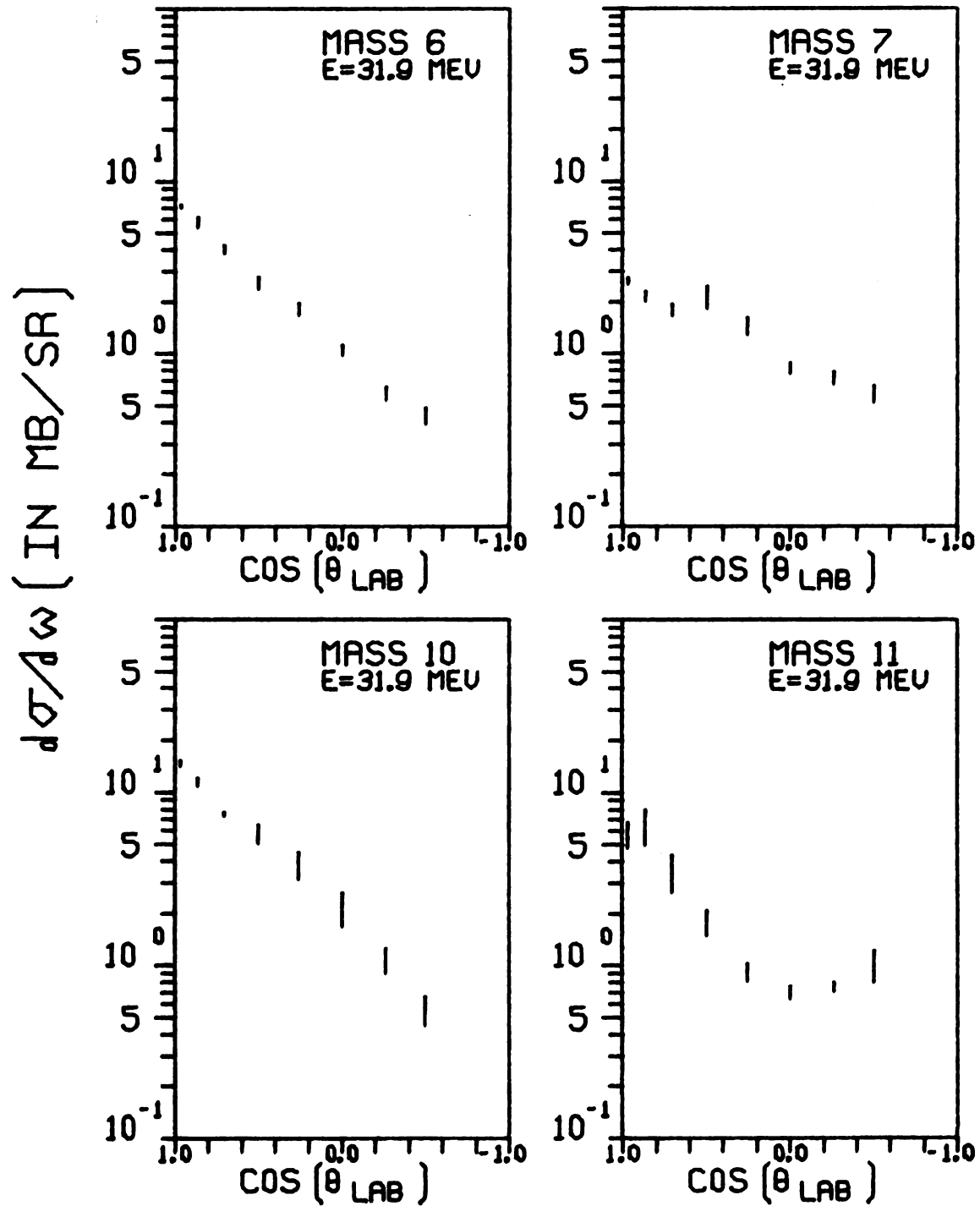


Figure 12. (continued)

ANGULAR DISTRIBUTIONS TARGET 14 N

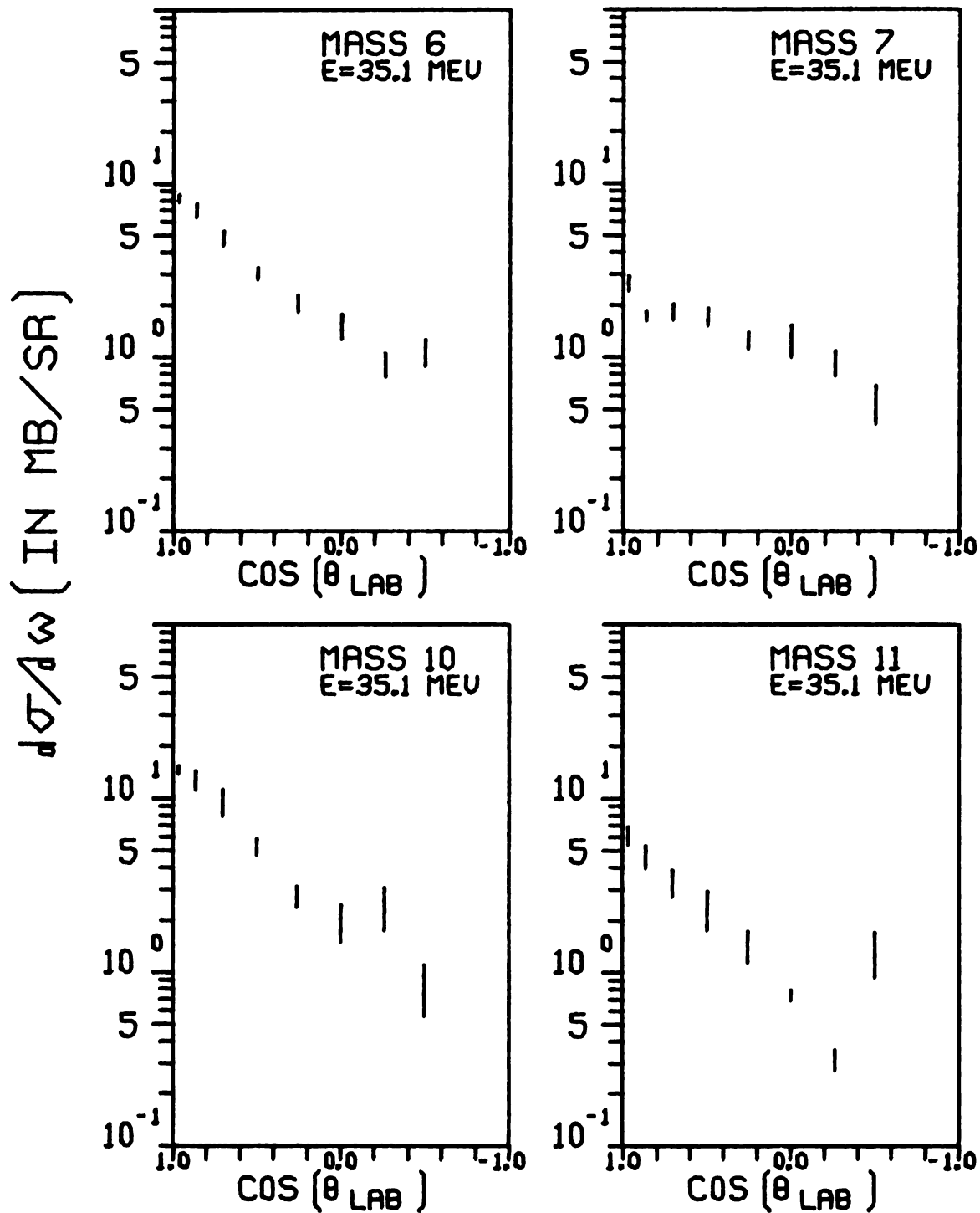


Figure 12. (continued)

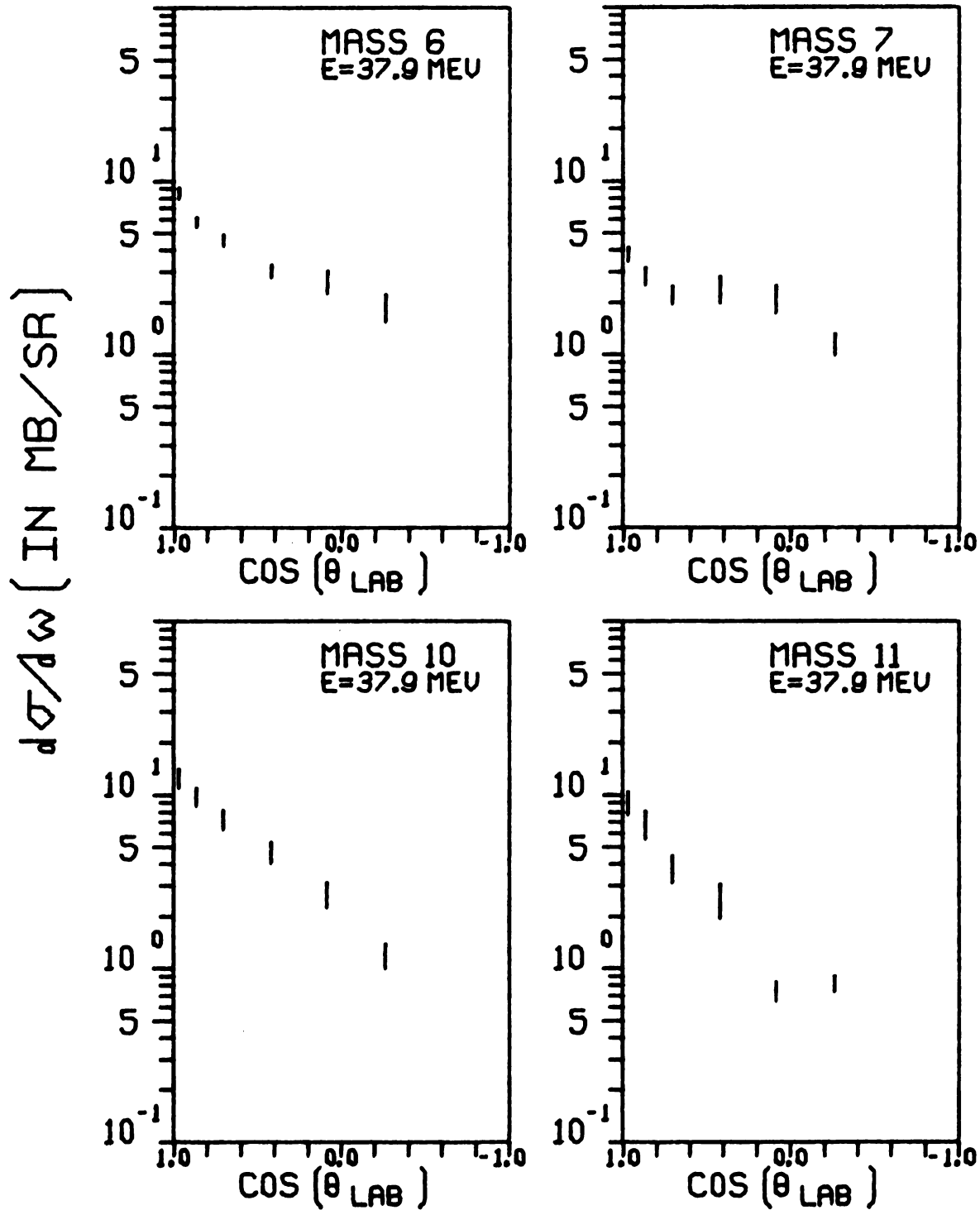
ANGULAR DISTRIBUTIONS
TARGET 14 N

Figure 12. (continued)

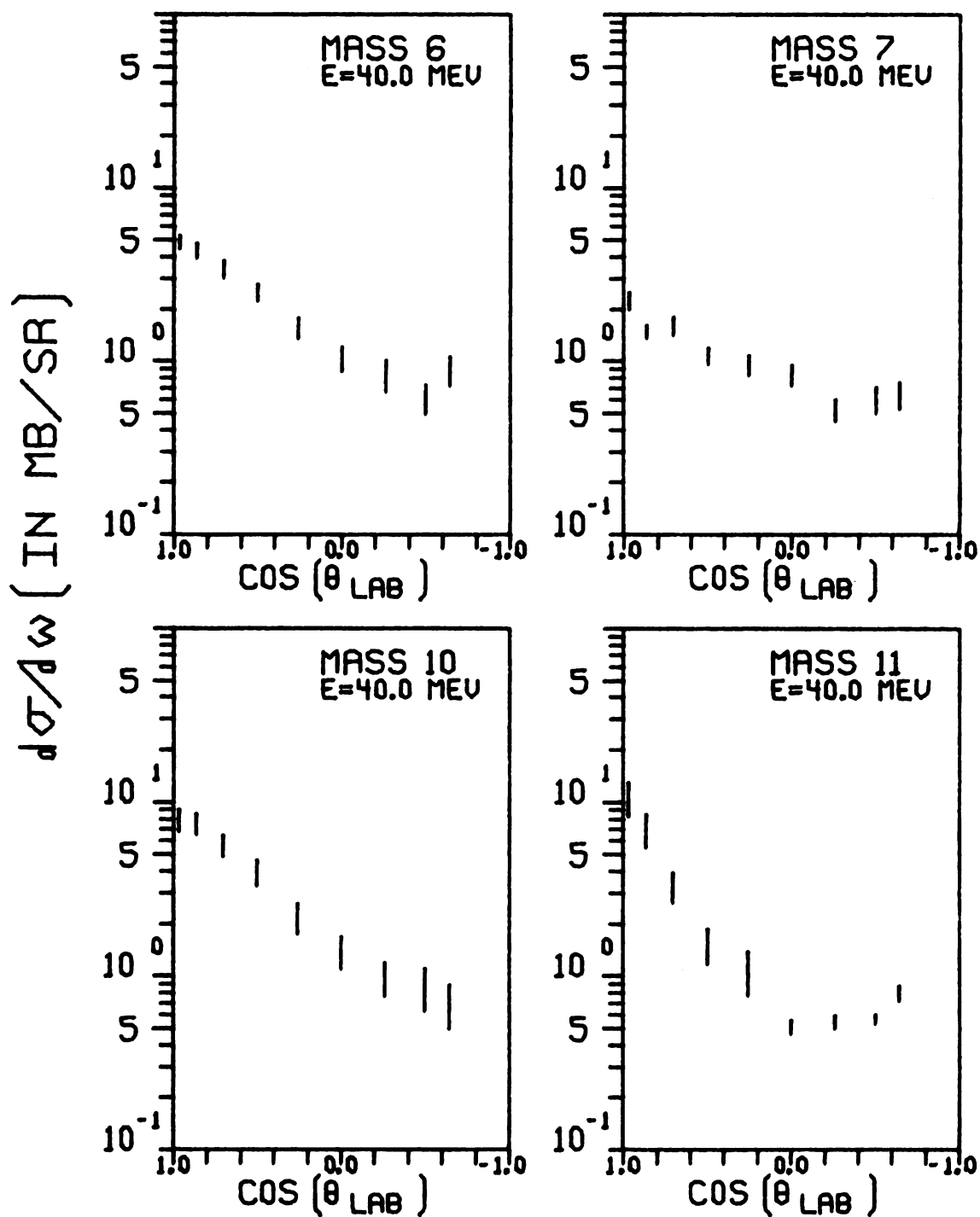
ANGULAR DISTRIBUTIONS
TARGET 14 N

Figure 12. (continued)

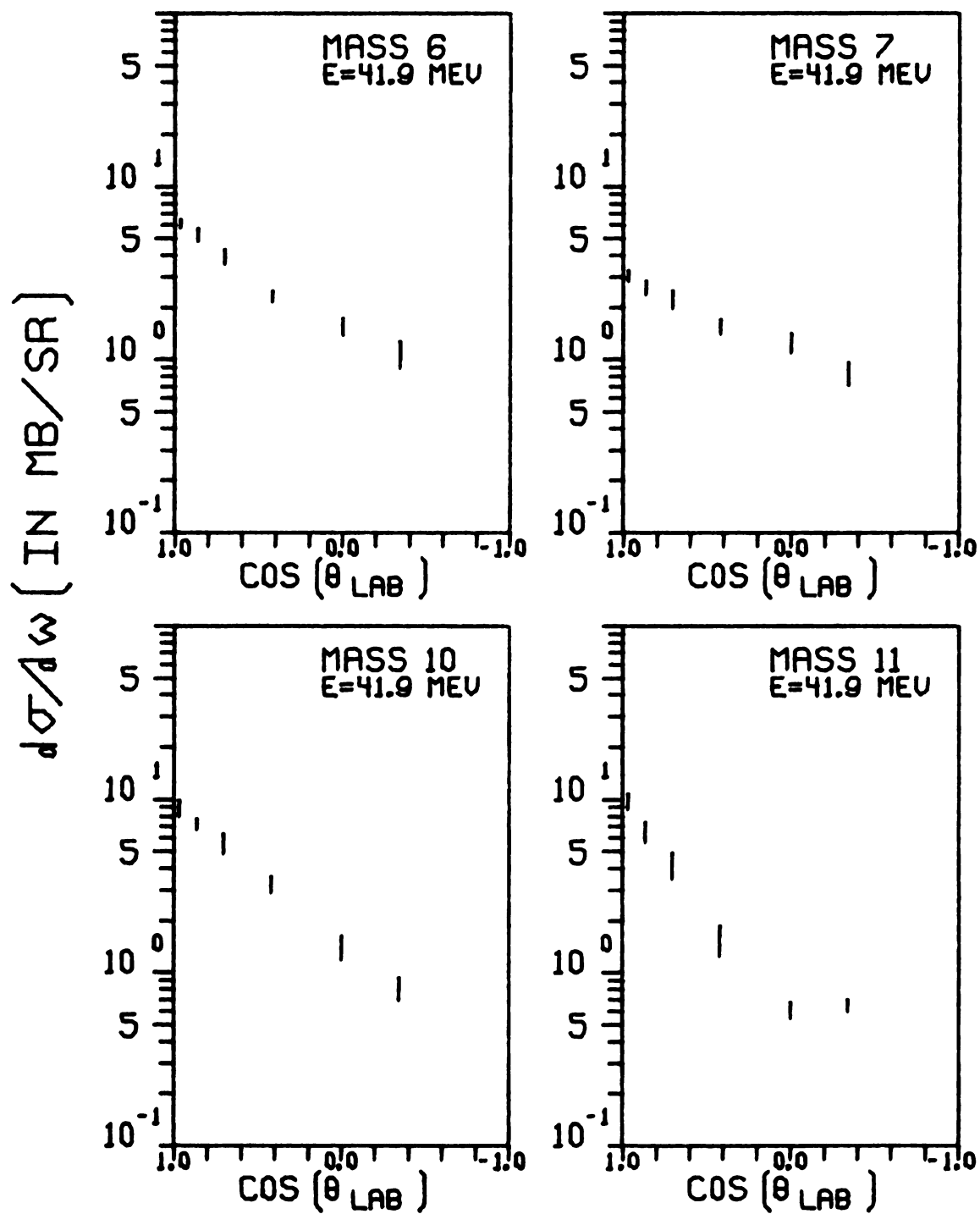
ANGULAR DISTRIBUTIONS
TARGET 14 N

Figure 12. (continued)

ANGULAR DISTRIBUTIONS TARGET 14 N

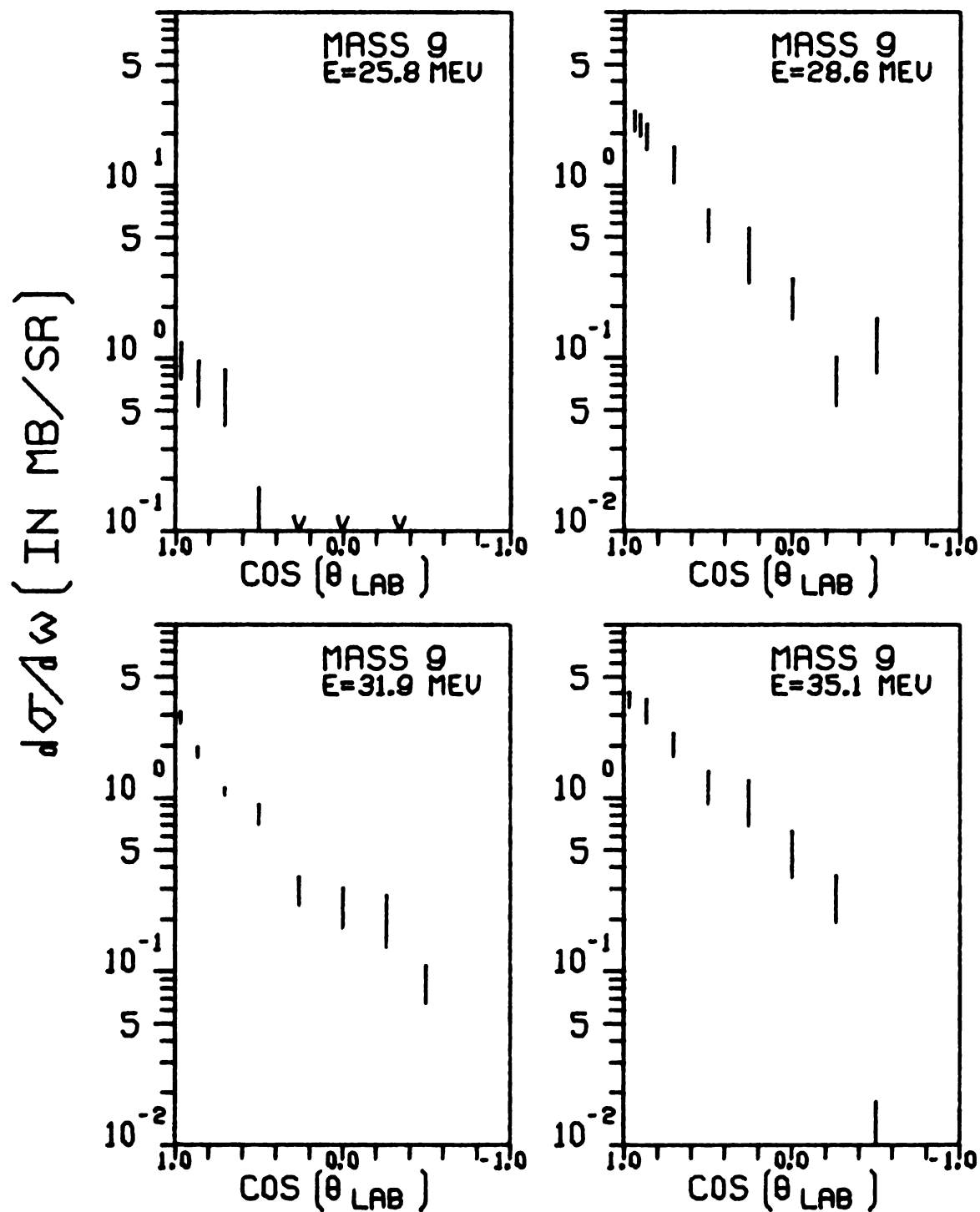


Figure 12. (continued)

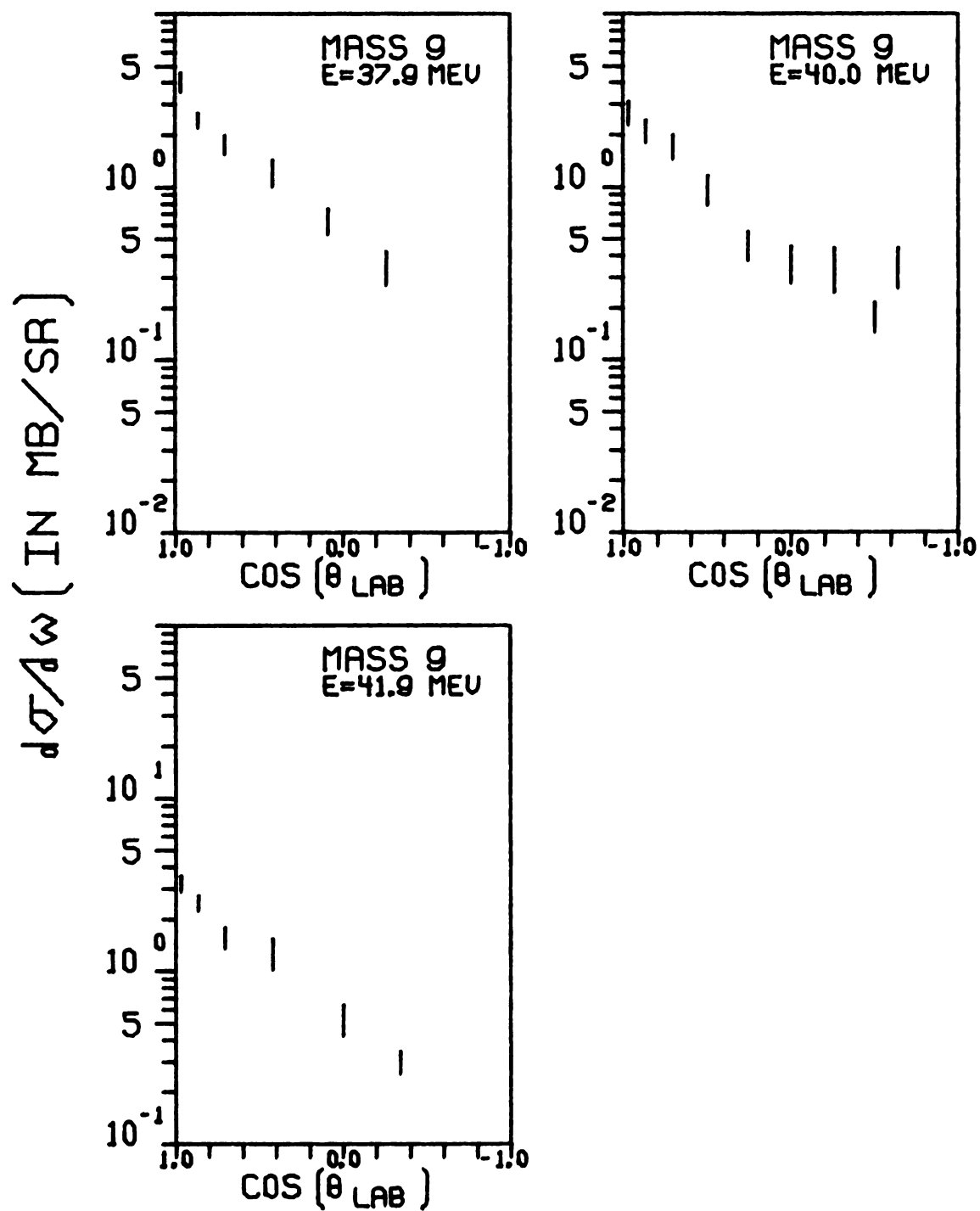
ANGULAR DISTRIBUTIONS
TARGET 14 N

Figure 12. (continued)

ANGULAR DISTRIBUTIONS TARGET 16 0

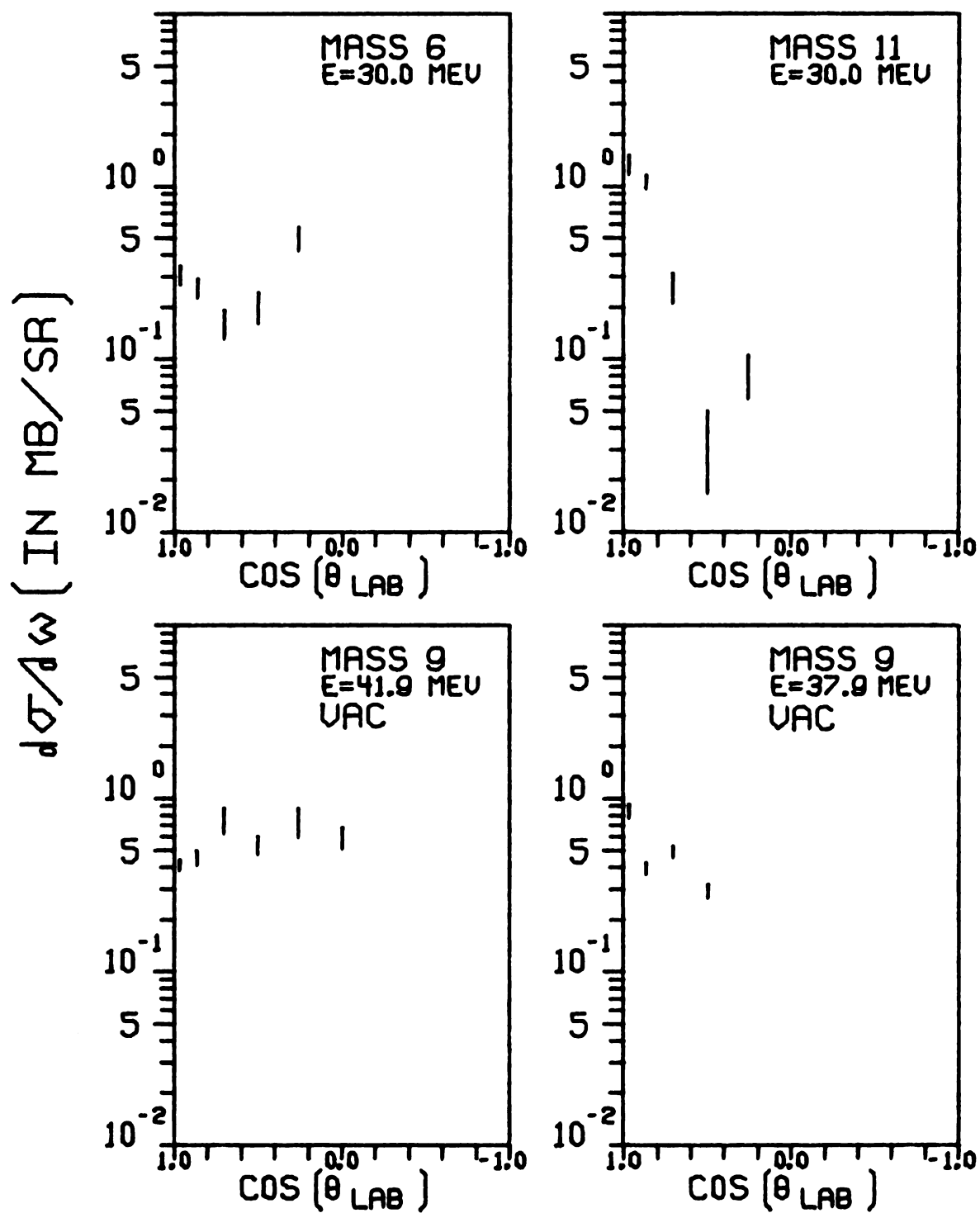


Figure 12. (continued)

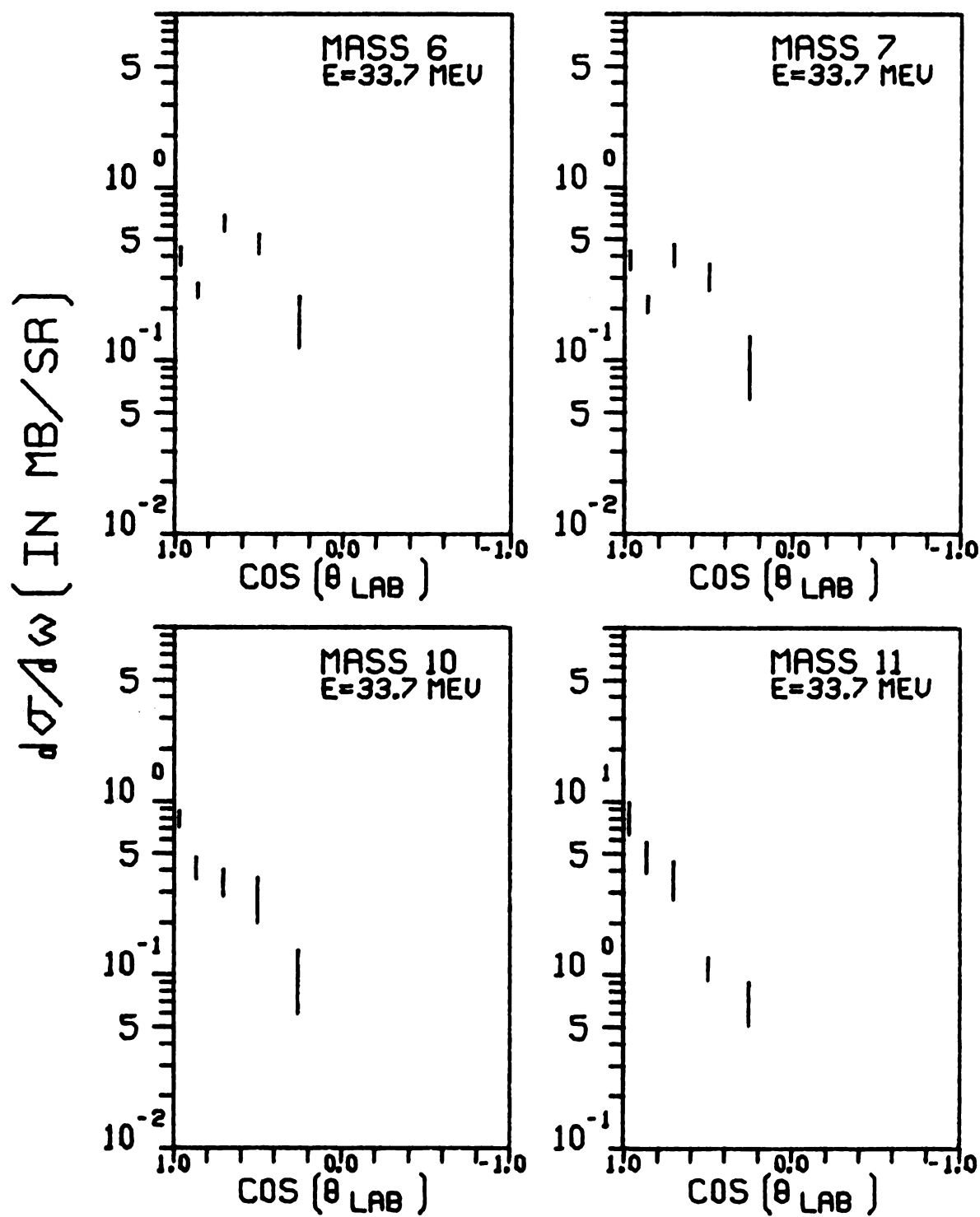
ANGULAR DISTRIBUTIONS
TARGET 16 0

Figure 12. (continued)

ANGULAR DISTRIBUTIONS TARGET 16 O

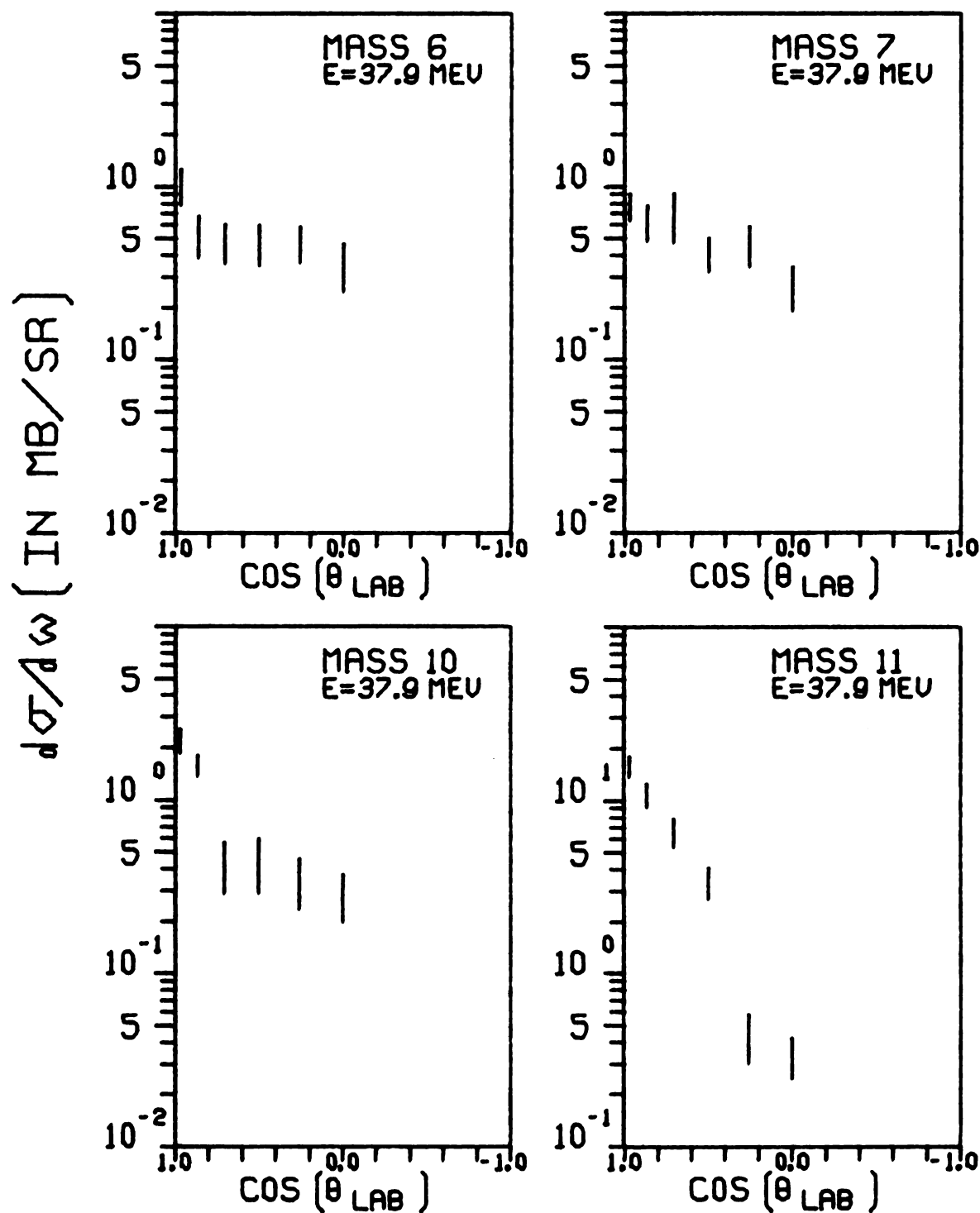


Figure 12. (continued)

ANGULAR DISTRIBUTIONS TARGET VAC

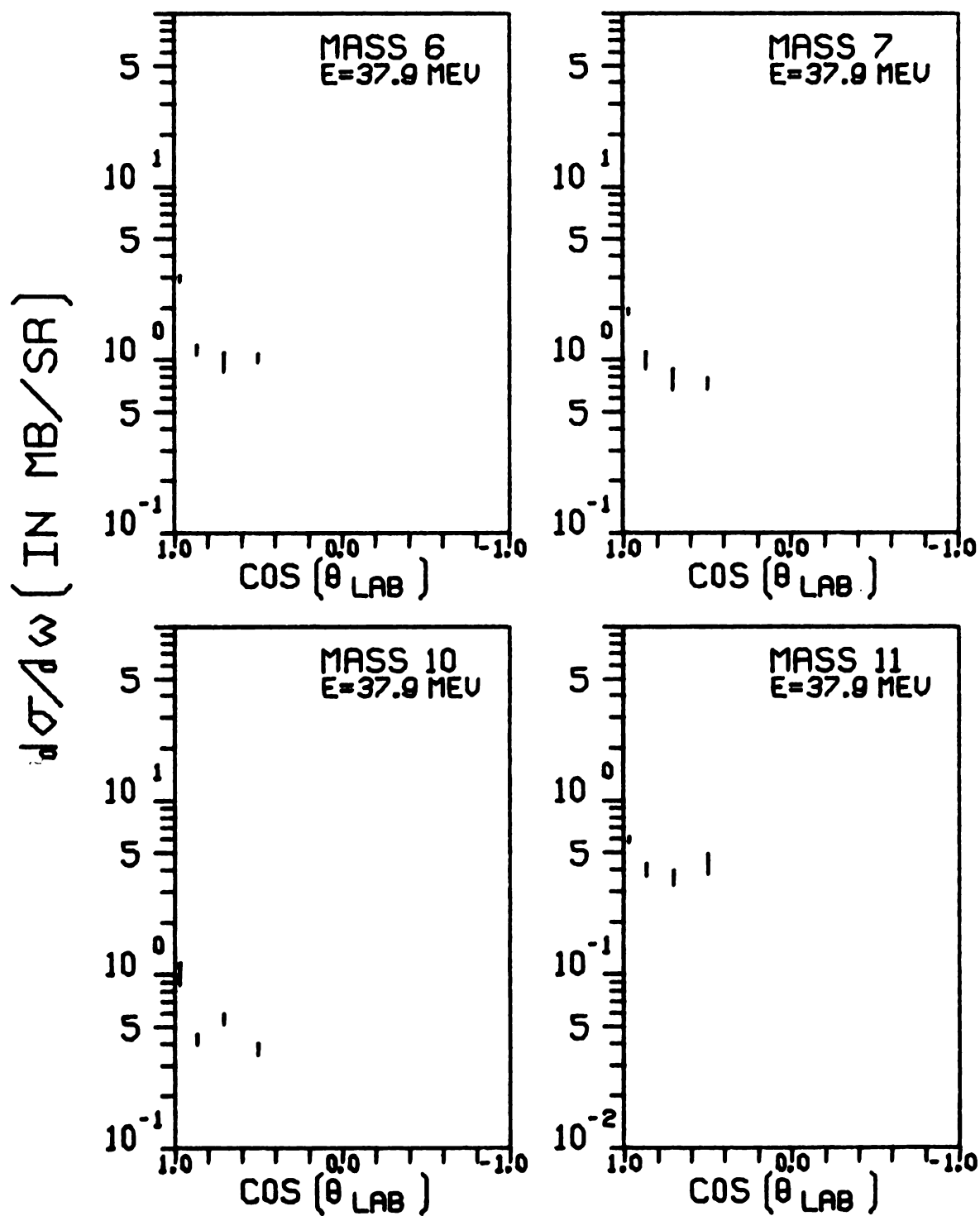


Figure 12. (continued)

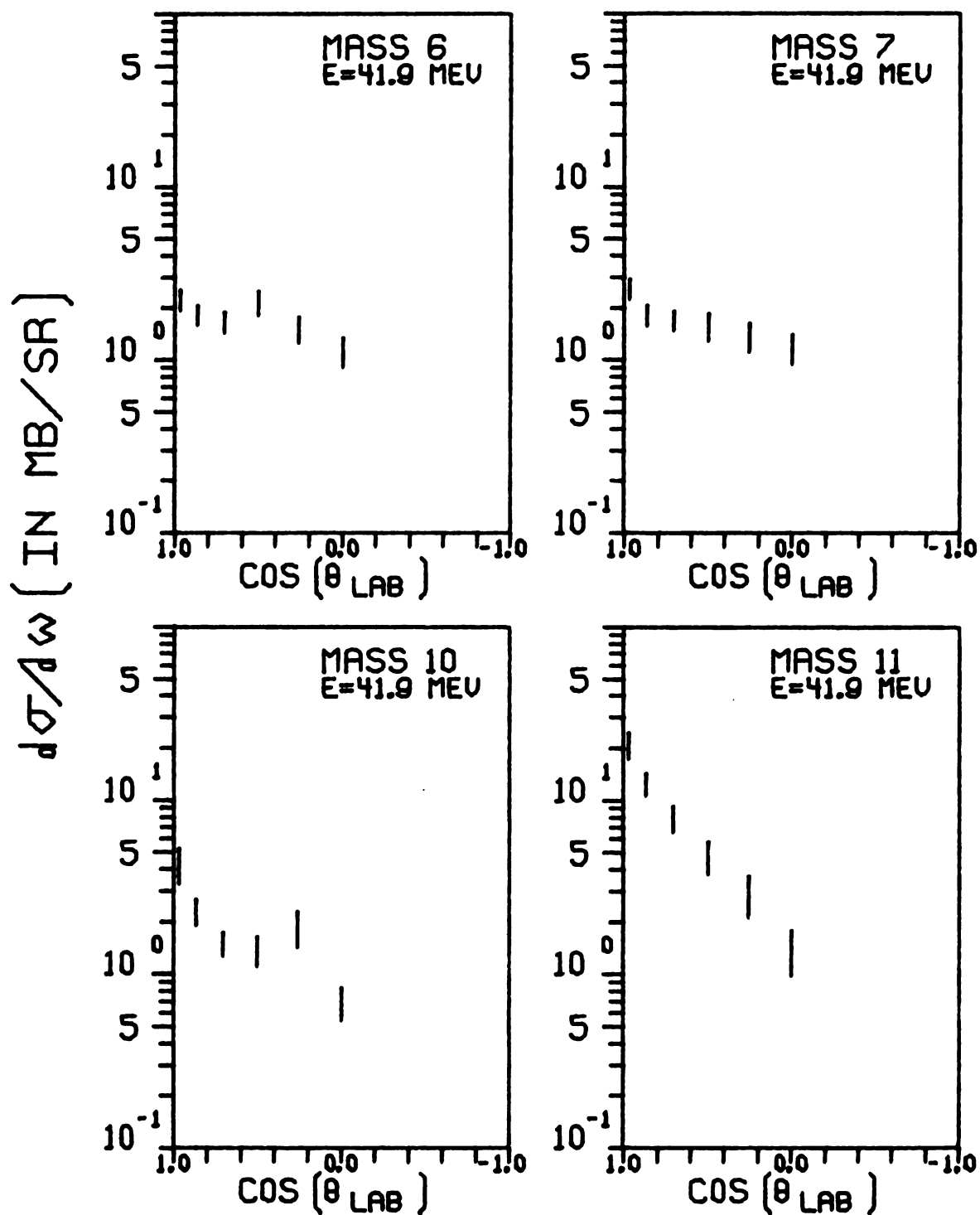
ANGULAR DISTRIBUTIONS
TARGET 16 0

Figure 12. (continued)

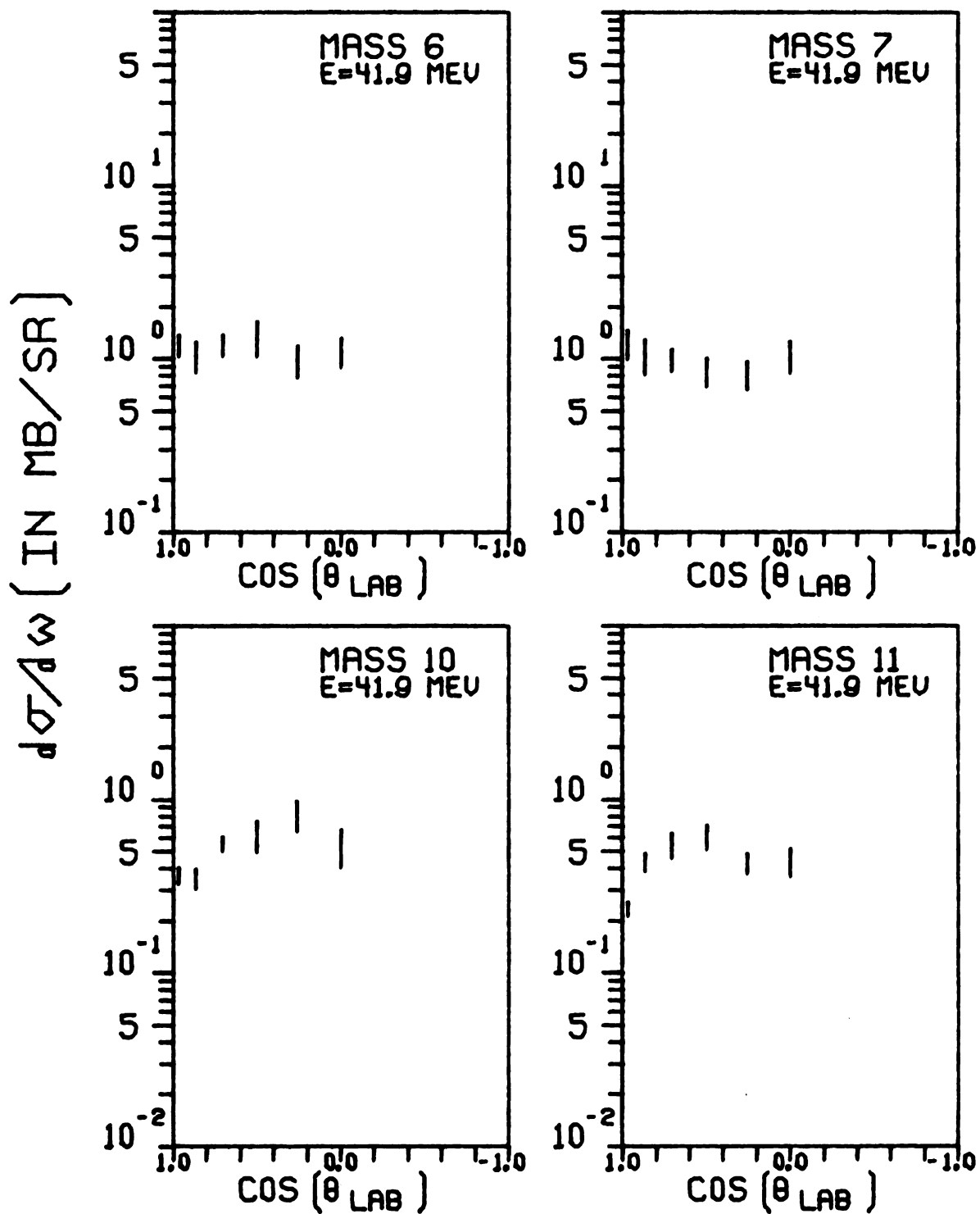
ANGULAR DISTRIBUTIONS
TARGET VAC

Figure 12. (continued)

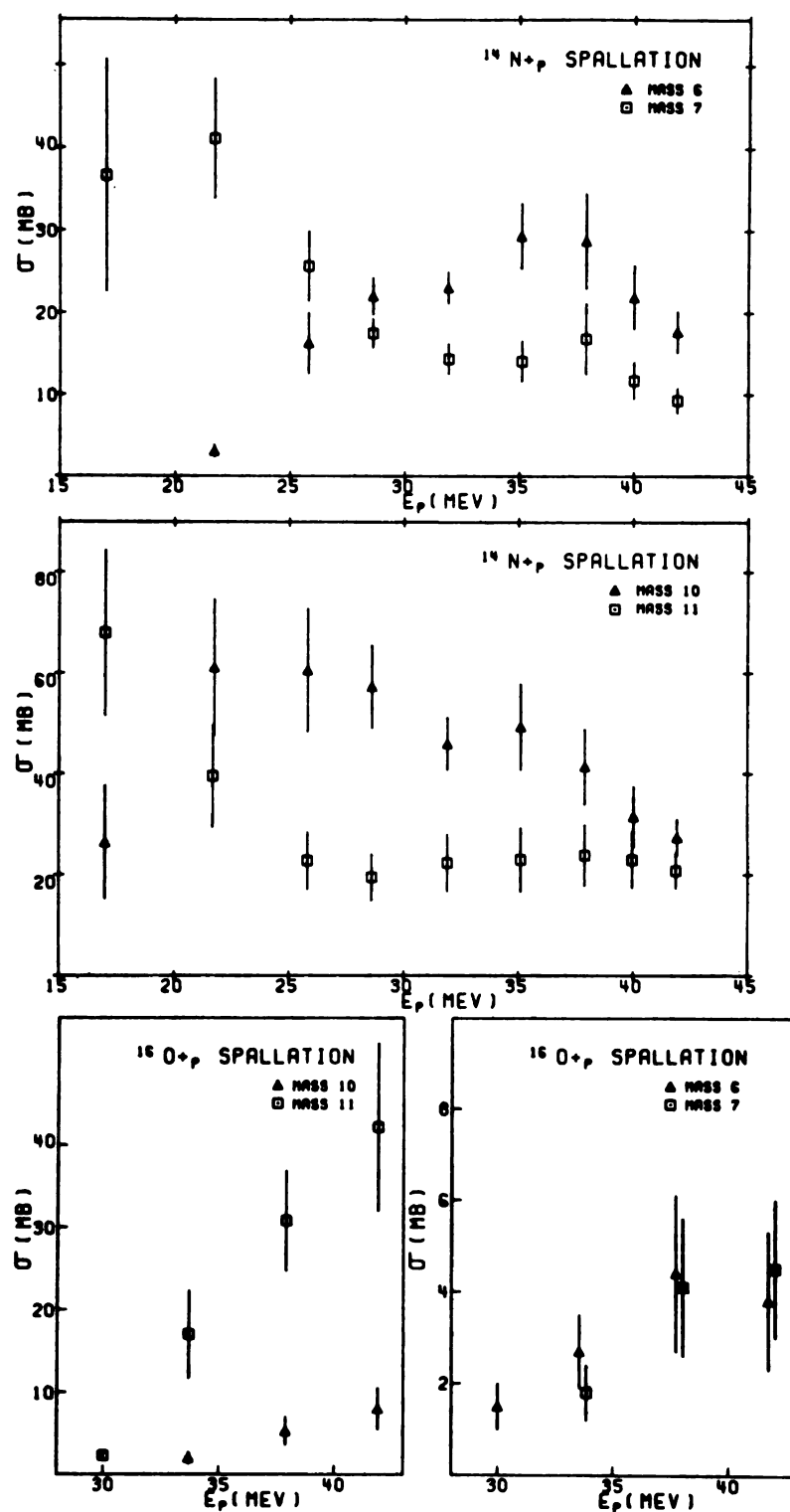


Figure 13. Cross-Sections for Masses 6,7,10,11 from Proton Spallation of Targets ^{14}N and ^{16}O in the Energy Range $E_p = 17$ to 42 MeV.

5. RADIOACTIVATION AND DECAY MEASUREMENTS

5.1 Introduction

Since the time-of-flight technique is limited by the low energy cutoff, it is desirable to have an alternate technique which could be used to check cross-sections at one energy. A 22 MeV proton colliding with a ^{14}N nucleus at rest makes 20.5 MeV available in the center of mass. This is just below the 20.7 MeV threshold for ^{11}B production. Thus the only mass 11 isobar produced at this proton beam energy is ^{11}C ; similarly the only mass 7 isobar made is ^7Be . The decay of ^{11}C is by β^+ emission with a half-life of 20.5 min, so its cross-section can be measured by counting 0.511 annihilation γ -rays. The decay of ^7Be is by electron capture with a half-life of 52.6 days, and $10.3 \pm 0.16\%$ (TM 62) of the time it decays to the 0.477 state in ^7Li ; so finding the intensity of this γ -ray yields the ^7Be cross-section.

5.2 Cell Construction

Finding a suitable nitrogen target is again an important consideration. A small gas cell with Kapton windows to hold the ^{14}N target gas was designed for γ -ray counting with a lithium-drifted-Ge detector. Figure 14 shows a diagram of the cell assembly. The Kapton windows are pressed against O-rings by the 1/16" thick aluminum disks. The ports, open during irradiation, are plugged with 1/16" aluminum disks when the γ -ray counting is done. The aluminum stops even the most energetic positrons from ^{11}C decay. Hence all γ -rays originate within the cell volume or on the inner

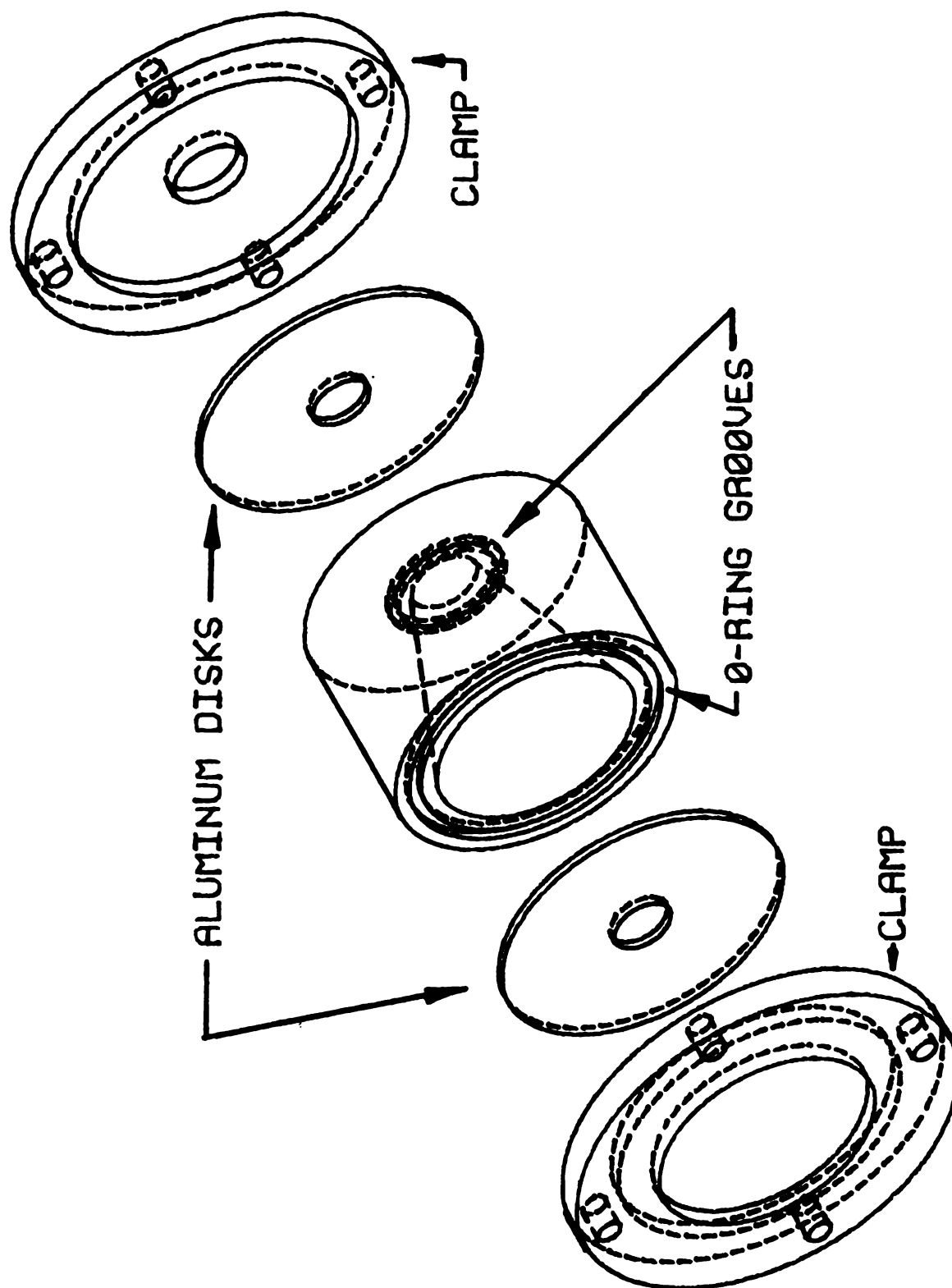


Figure 14. Partial Assembly Drawing of Gas Cell for Activation and γ -ray Counting.

walls. The frustum design was chosen so no γ -ray has to go through more than $1/16$ " of aluminum plus $1/16$ " of brass (^{11}C positrons penetrate up to 0.5 mm of brass before annihilation) to get to the detector. A γ -ray intensity attenuation correction can thus be made with confidence. Assuming the average ^{11}C γ -ray traverses 1.5 mm of aluminum and 0.75 mm of brass (one-half the maximum possible) the attenuation correction factor is 1.091. In the absence of a proper averaging procedure I assign an error of $\pm 3\%$ to this number. For the ^7Be γ -ray which only traverses 1.5 mm aluminum the correction factor is 1.036 with better than 1% accuracy.

A 9559B-1MM Circle Seal valve with a $1/4$ " Eastman Poly Flow fitting was soldered directly into the cylinder of the cell body (not shown in Figure 14). The volume of gas in the closed valve is less than 1% of the total cell volume. Hence the resulting counting error due to asymmetry of the volume holding the radioactive gas is quite negligible.

The Kapton windows are the main source of 0.511 MeV and 0.477 MeV background γ -rays. However a minimum thickness of Kapton is needed to stop ^{11}C and ^7Be from escaping the cell. For ^{11}C , 0.0005" Kapton windows are sufficient to stop even the forward scattered nuclei. For the ^7Be measurement 0.001" Kapton had to be used as exit window to accomplish the same purpose (Appendix A).

5.3 Irradiation Technique

For each cross-section measurement two irradiations were performed. Two identical gas cells were prepared. One cell was filled with ^{14}N , its twin with ^4He . The pressure was chosen to be 1 atmosphere so that no stress was exerted on the cell windows before and after irradiation. The chance that leaks would develop was minimized in this way. With the ^4He filled cell the contribution to the total yield by the Kapton was determined. A Helium filled cell rather than an empty one was used to ensure that any changes in the Kapton are similar for both irradiations. The most important effect is due to heating. Kapton in vacuum and in contact with a gas should have different equilibrium temperatures. Also the stress of 1 atmosphere pressure on the heated Kapton may deform it.

5.4 Counting Method for ^7Be and ^{11}C Decays

The γ -rays were counted with a lithium drifted Ge^1 detector. An electronics block diagram is shown in Figure 15. For good counting geometry the gas cell was placed at 10 inches from the detector. The detector efficiency at this distance was established for the 0.511 γ -ray using a standard ^{22}Na source (from the Bureau of Standards, 5% accuracy quoted). The relative efficiency of the 0.477 MeV γ -ray with respect to the 0.511 MeV γ -ray was found by assuming $\log(\gamma\text{-energy})$ vs. $\log(\text{relative efficiency})$ is a

¹Manufactured by Nuclear Diodes, Prairie View, Ill.; Relative peak efficiency 10.4%.

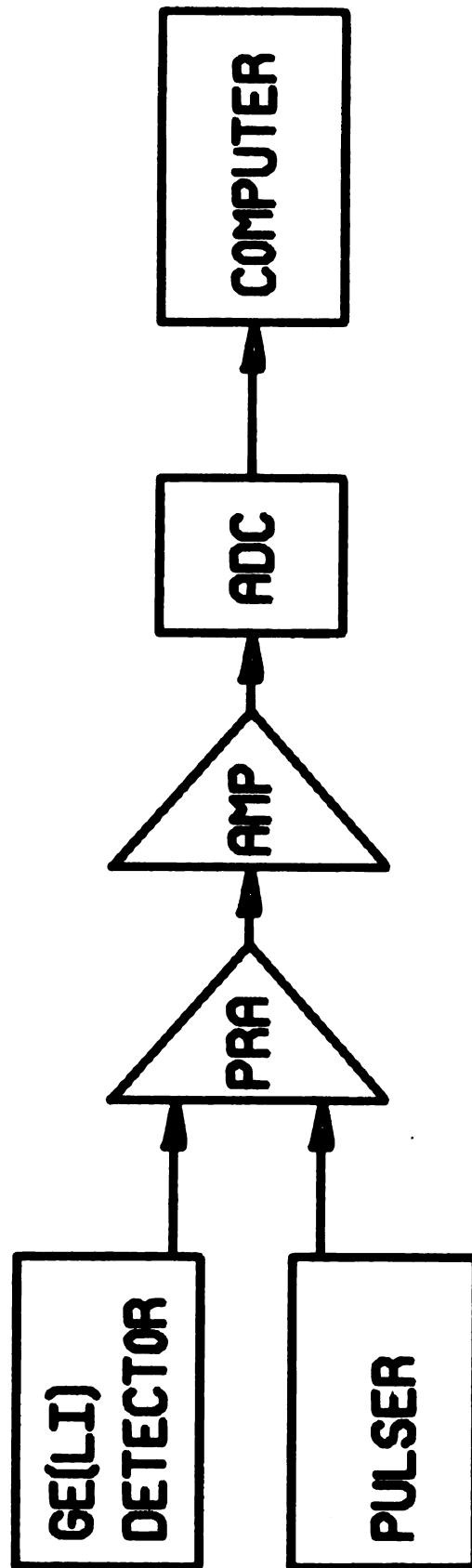


Figure 15. γ -Ray Counting Electronics Block Diagram.

straight line, determined by the 0.511 MeV γ -ray and the 1.274 MeV γ -ray of ^{22}Na . A Ge(Li) detector for which a more complete efficiency curve is available (DO 70) exhibits this relationship in the range from 200 keV to 5 MeV.

The β^+ decay γ -ray origin, and the frustum geometry of the cell make precise positioning difficult. Consider case 1, γ -rays originate from all inner cell surfaces with equal likelihood or, case 2, γ -rays originate from the gas volume only. To effectively place the cell at 10" from the detector I find the cell position for the first case is 0.024" closer to the detector than for the second case. This still represents a negligible error of 0.24% in distance or $\approx 0.5\%$ in cross-section.

In the case of ^7Be the irradiation time is short compared to the half-life. For a cross-section calculation one then needs the gas pressure, the total charge traversing the cell and the distance traveled by the beam in ^{14}N . In section 5.7 these measurements are combined with the measured γ -decay rate, detector efficiency and branching ratio to yield the ^7Be total cross-section. The 0.477 MeV γ -rate was measured by counting for 4 hours each on the ^{14}N filled and ^4He filled gas cells. The counting was done at least 24 hrs after irradiation so that the background due to annihilation 0.511 γ 's was low. The γ -ray was identified by its energy and by its 53 day half-life.

^{11}C has a half-life of 20.5 min. An adequate irradiation consisted of 500 namp of proton beam for a duration of

10 minutes. Beam intensity fluctuations can therefore not be neglected. A chart recorder running at 3 in/min was used to record the instantaneous beam intensity.

The ^{11}C counting was started 3 minutes after irradiation. Counting was continued for 3 hrs.; intervals were chosen to be a 5 min. step followed by 10 min. steps. A pulser with the frequency of 19.1 counts/sec was injected into the detector preamplifier and was used to correct for deadtime losses.

5.5 Data Reduction

The 0.511 MeV γ -decay curves for (Kapton + ^4He) and (Kapton + ^{14}N) show that besides the 20.5 minute component there are shorter and longer half-lives involved (see Figure 16). Care had been taken during irradiation and counting that both gas cells had received the same treatment. Hence the decay curve for the ^4He filled cell could be subtracted point for point from the one for the ^{14}N filled cell. Since protons bombarding ^4He do not lead to products which β^+ decay, the difference curve for the two cells then represents the contribution of ^{14}N proton spallation products to β^+ decay.

At 22 MeV bombarding energy the only relatively long lived radioactive isotopes from $^{14}\text{N}+\text{p}$ which contribute to the 0.511 MeV annihilation radiation are ^{13}N with a half-life of 9.96 min and ^{11}C with a half-life of 20.5 minutes. $^{15}\text{O}(124\text{s})$, $^{14}\text{O}(71\text{s})$, $^{10}\text{C}(14\text{s})$ are also produced but have much shorter half-lives. The decay curves and their

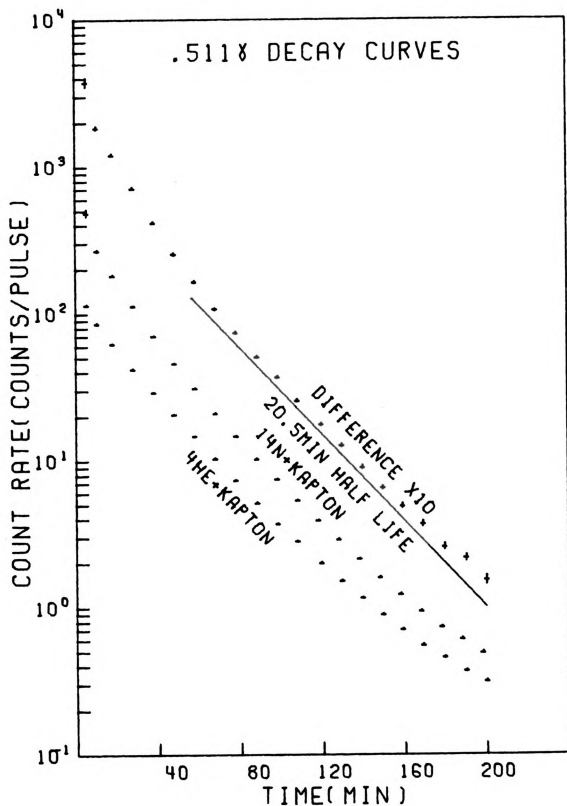


Figure 16. Data Points of 0.511 γ Decay Curves for Nitrogen and Helium Filled Gas Cells and the Curve Resulting from Taking their Difference.

difference is shown in Figure 16. The line shown represents a 20.5 min half-life and is only included as a reference. It can be seen that shorter and longer half-lives are present. The shorter half-lives can be understood since they may be present as pointed out above. The longer half-life must represent a difference in irradiation between the cells and is not understood at present. The error introduced in determining the 20.5 min half-life intensity is 10%. In Figure 17 a number of fits to the difference curve are shown with the fit parameters given for each curve. The time scale is only valid for the left most data set. Other curves were displaced to the right for display purposes. The crosses in Figure 17 represent the data. We consider half-lives 10 min, 20.5 min and also a longer half-life, either 41 min or 324 min. For a fit using two half-lives we select two data points; for three half-lives we need three data points. The selected points, boxed in Figure 61, determine counting rate contributions of the different half-life components. The solid line represents the calculated counting rate. The contributions by the 20.5 min component at 41 min after the end of irradiation to the fits shown in Figure 61 are from left to right, 487, 460, 394, 430, and 435 counts/sec. We use the value 438 ± 45 counts/sec in our cross-section calculations.

5.6 Cross-Section Calculations for ^{11}C

To calculate the ^{11}C production cross-section from the observed rate after irradiation, the decay of ^{11}C during

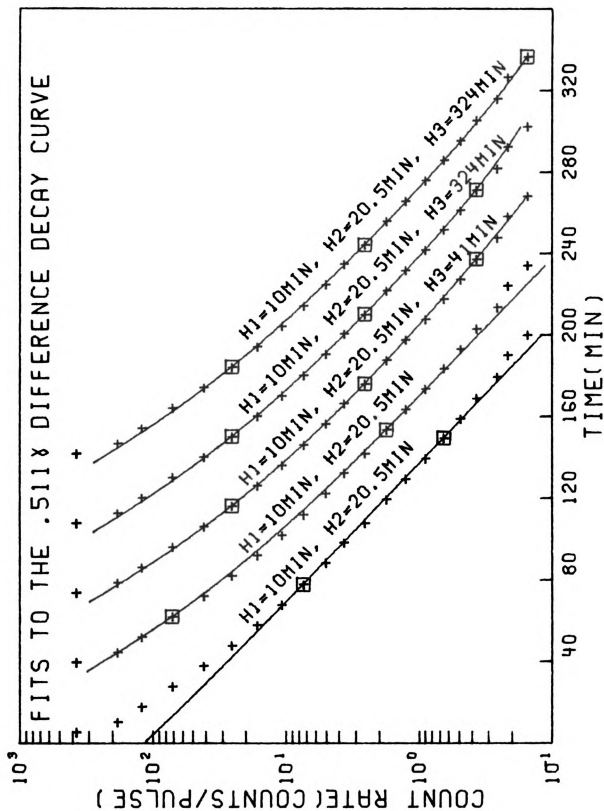


Figure 17. Sample Fits to the 0.511 γ Difference Decay Curve.

irradiation has to be taken into account. A numerical integration fortran program was written based on the equation:

$$dN = \frac{-N \log 2}{H} 2^{-\Delta t/H} \Delta t + \sigma n_t \Delta n_i$$

dN represents the net change in the number of ^{11}C nuclei during the time interval Δt .

N is the number of ^{11}C nuclei present at the beginning of Δt .

H is the half-life;

σ is the total cross-section for spallation production of ^{11}C .

n_t is the number of target nuclei per cm^2 .

Δn_i is the total number of incident protons during the time interval Δt .

The program is given an arbitrary value for σ such as 1 mb, and it starts by calculating dN for the first second of irradiation. This becomes the value of N during the next second after which the new dN is added to N . This is done in one second time steps to the end of irradiation. The γ counting rate at 2 half-lives after the end of irradiation is then calculated. The correct value for the cross-section is then given by:

$$\sigma = 1 \text{ mb } \frac{\text{observed rate}}{\text{calculated rate}}$$

The irradiation histories for the ^{14}N and the ^4He activations yield cross-sections which differ by only 0.37% justifying the direct subtraction technique explained in section 5.5.

5.7 Cross-Section Calculations for ^7Be .

The decay of a radioactive nucleus is governed by the well known equation :

$$N = N_0 2^{-t/H}$$

N_0 is the number of radioactive nuclei present at time $t = 0$.

H is the half-life of the nucleus considered.

The decay rate is then given by

$$\frac{dN}{dt} = - \frac{\log 2}{H} (N_0 2^{-t/H})$$

The initial number of nuclei $N_0 = \sigma n_t n_i$.

In our case σ is the total cross-section for ^7Be production from ^{14}N . The total number of incident protons, n_i , is related to the collected charge Q (coulombs) by

$$n_i = Q / (1.6021 \times 10^{-19} \text{ coulombs})$$

and n_t , the total number of target nuclei/cm², for ^{14}N gas is given by

$$n_t = \ell P \frac{273.1}{T} (2) (2.687) \times 10^{+19} \text{ cm}^{-2}$$

The quantity P is the gas cell pressure in atmospheres,

T is the gas temperature in °K,

ℓ (cm) is the total length of gas traversed by the beam.

We measured ℓ by pressurizing the cell to 1 atmosphere above atmospheric pressure and measuring the distance between Kapton windows with a micrometer. P was the pressure of the atmosphere at the time of filling the gas cell. This was corrected for billowing of the windows when the cell is placed in vacuum.

The rate measured by the counter for a γ -ray from one source is:

$$R = \frac{\log 2}{H} (N_0 2^{-t/H}) X \epsilon G = \frac{dN}{dt} X \epsilon G$$

X is the number of γ 's per decay. For ^7Be this is equal to the branching ratio to the 0.477 MeV level in ^7Li ; $X = 0.103$. ϵ is the photopeak efficiency of the detector for a point source at 25.6 cm, G is a geometric factor taking account of the finite extent of the gas cell, N_0 is the number of radioactive nuclei present at time $t=0$ and H is the half-life of the nucleus considered.

ϵ was found by counting γ -rays from a N.B.S. calibrated ^{22}Na source rated at 1.62 $\mu\text{curies} \pm 5\%$ on 11-11-70. The efficiency measurement was performed on 3-21-71. The center of the source was placed 25.6 cm from the Ge detector. 653500 \pm 2500 counts were accumulated in the 0.511 γ -ray peak. 162500 \pm 700 counts were accumulated in the 1.274 γ -ray peak. 194200 counts were accumulated in a peak due to a pulser running at 5 pulses/sec.

The error assignments are obtained from $\sqrt{\text{counts in Peak} + 2\text{Background}}$. $G=1$ can be assumed for the source since it is quite small. $X=1.8$ for the 0.511 γ -ray and $X=1.0$ for the 1.274 γ -ray.

From this data and the assumption that the logarithm of the γ -ray energy vs. the logarithm of the relative efficiency traces out a straight line, $\epsilon = 1.818 \times 10^{-4}$ is obtained for the absolute efficiency of the 0.477 γ -ray from ^7Be .

The constants for the equation used to relate decay rate to ^{11}C cross-section are mostly the same as those for ^7Be . The photopeak efficiency for the 0.511 γ -ray is 1.714×10^{-4} . The half-life for ^{11}C decay was taken to be 20.5 min. X , the number of γ 's per decay, is equal to 2.0.

5.8 Error Analysis

Table 11 summarizes error contributions to the cross-section determination by radioactivation-decay measurements.

5.9 Cross-section Comparison

Table 12 compares our 21.7 MeV ^{11}C and ^7Be cross-section measurements by the time-of-flight and γ -counting methods, as well as the recently published values (ES 71), (BCJR 71). There is agreement within the quoted errors. From the Epherre data it is also apparent that the ^{11}C cross-section falls rapidly with increasing proton beam energy near 21 MeV; hence, the marginal agreement for ^{11}C is not unexpected. Our 17 MeV ^{11}C time-of-flight data does not agree with the Epherre data, but error bars almost meet at 87 mb.

Table 11. Error Contributions to the Radioactivation-Decay Measurements.

Error Source	Error in %	Comments
ϵ efficiency	6.0	
P pressure	0.5	From Lansing Weather Bureau Station
T temperature	1.5	
d distance of detector from cell	0.24	Explained in Section 5.4
ℓ distance beam travels in ^{14}N	0.5	Micrometer measurement
Q integrated charge	3.0	
$R_{^{11}\text{C}}$ decay rate after irradiation	10.3	
$R_{^7\text{Be}}$ decay rate after irradiation	3.0	
$X_{^7\text{Be}}$ branching ratio	1.6	(TM 62)
γ attenuation for ^{11}C	3.0	
γ attenuation for ^7Be	1.0	

Added in quadrature the error for the ^{11}C cross-section is then 13% and the error for the ^7Be cross-section is 8%.

Table 12. ^{11}C and ^7Be Cross-section Measurement Comparison.

Cross-sections at 21.7 MeV in mb				
	Radioactivation γ counting	Time-of- Flight	Epherre et al. (ES 71) Read from a graph	Bodansky et al. (BCJR 71) 20 MeV
^{11}C	36.2 ± 4.5	39.5 ± 10.1	50 ± 12	
^7Be	49.0 ± 3.8	41.2 ± 7.2	45 ± 8	46 ± 5
Cross-sections at 17 MeV in mb				
^{11}C		69 ± 16	110 ± 27	
^7Be		36.6 ± 14	30 ± 5	

6. REVIEW OF PAPERS ON ASTROPHYSICAL THEORIES OF LiBeB PRODUCTION

6.1 Introduction

A complete theory of LiBeB production has to explain abundances and isotopic ratios encountered in nature. Table 13 is a short compilation of the presently available data of importance to the theories on L(LiBeB) nuclei production. The following pages give a short history of light element synthesis theories by reviewing excerpts of papers on the subject. The values used often vary somewhat from those in Table 13, but the conclusions drawn in the various papers are not sensitive to changes of that magnitude.

6.2 Early Theories of Nucleosynthesis of LiBeB

The early theories of nucleosynthesis recognized that there was difficulty in producing the light elements even in their comparatively low abundances. In 1955 Hayakawa (Ha 55) and Fowler et al. (FBB 55) proposed stellar surfaces as a creation site with high energy protons causing spallation of the heavier constituents of the stellar atmosphere. Fowler et al. considered two possibilities. They envisioned hot spots in magnetic spots where $\rho = 10^{-8} - 10^{-7} \text{ g/cm}^3$ and $kT \approx 5\text{MeV}$ and claimed under these conditions $(\text{Li}, \text{Be}, \text{B})/(\text{C}, \text{N}, \text{O})=1$, the observed galactic cosmic ray ratio. They then weakened this hypothesis by observing that in Apm stars, the proposed site for the magnetic activity, the low Be abundance speaks against this mechanism. The second possibility considered was proton spallation of C,N,O at energies $> 100 \text{ MeV}$ in regions

Table 13. Abundances of Interest in LiBeB Production.

Element or Isotope	Abundances ($H = \text{Log } \epsilon_H = 12$)		
	Solar System (CA 67)	Sun (MU 68)	Sun
H	12.00	12	
He	10.91		
^6Li	2.11		{ .29 (PE 68)
^7Li	3.21	< .9	
^9Be	1.42	2.34	
^{10}B	1.67		
^{11}B	2.28	< 3.6	
C	8.72	8.51	
N	7.97	8.06	
O	8.96	8.83	
Ne	7.96		
Si	7.59	7.70, 7.24	

RatiosIn Cosmic Rays

$$\text{LiBeB}/n_{\text{CNO}} = .24 \quad (\text{GMS } 70)$$

$$\text{Li:Be:B} = .5:.45:1 \quad (\text{FGS } 68)$$

In Sun (MU 68)

	Photosphere	Corona UV	Solar Cosmic Rays
C/N	2.8	10	3.1
O/N	5.9	7.7	5.3
$^6\text{Li}/^7\text{Li}$	≤ 0.05		

Table 13. (continued)

In Rocks (Earth) and Meteorites

$$^7\text{Li}/^6\text{Li} = 12.5$$

$$^{11}\text{B}/^{10}\text{B} = 4.0$$

of $\rho < 10^{-9}$ g/cm³. For either of these, Apm stars were found to be too few in number to account for the cosmic abundance.

They then considered the possibility of this spallation mechanism in M dwarfs being the source of the light elements. They assumed M dwarfs contributed all of the LiBeB and 5×10^{-5} of the total cosmic abundance of matter in a time span of 10^9 years. To produce the observed abundance of LiBeB, the ratio of (Li,Be,B)/(C,N,O) in the ejected material must be in the range 10^{-3} - 10^{-2} . This represents 0.1 to 1 percent efficiency assuming a ratio of one is the maximum possible attainable by spallation of C,N,O in the gas. However since the magnetic activity of M dwarfs is much less than that of Apm stars the authors did not feel it was evident that this ratio could be achieved in the ejected material.

In the classic paper on the synthesis of elements in stars Burbidge, Burbidge, Fowler, and Hoyle (BBFH 57) still found stellar atmospheres a possible synthesis site, but they also considered gaseous nebulae and supernovae as possible candidates. No calculation for the latter two were attempted. In this paper there was also speculation that ^7Li may be synthesized in helium burning cores of late-type stars by $^3\text{He}(\alpha, \gamma) ^7\text{Be} \xrightarrow{\text{K captures}} ^7\text{Li}$. The ^7Li can be brought to the surface provided the hydrogen envelopes only extend to depths where the temperature is less than $\sim 10^6$ degrees.

In 1960 a paper by W. K. Bonsack and J. L. Greenstein (BG 60) on the abundance of lithium in T-Tauri stars gave new impetus to spallation-at-the-surface-of-stars theories.

They found that the Li abundance in T-Tauri stars is about 100 times the solar value or about the same as observed terrestrially. They also observed that the surrounding nebulae have at least ten times less lithium per gram than the T-Tauri atmosphere, which strongly suggests that Li is made in the star. A number of calculations were performed in this paper.

To check whether cosmic ray Li could be the source of stellar Li they started with the cosmic ray number ratio $(\frac{\text{Li}}{\text{H}})_{\text{cr}} = 10^{-3}$, a cosmic ray energy density $U_{\text{cr}} = 1 \text{ ev/cm}^3$ and a mean cosmic ray energy of $\bar{E} = 10^9 \text{ ev}$, and the particle density of hydrogen $n_{\text{H}} = 1/\text{cm}^3$. After condensation the Li/H ratio due to cosmic ray Li abundance is then

$$\frac{\text{Li}}{\text{H}} \leq 10^{-3} \frac{U_{\text{cr}}}{\bar{E} n_{\text{H}}} \leq 10^{-12}$$

which is compared to the approximate solar abundance ratio 10^{-11} and hence is found to be too low even for normal stars.

The authors also attempted to calculate the energy required of each star to produce the observed high-abundance of $\frac{\text{Li}}{\text{H}} = 10^{-9}$. They assume 100 MeV is needed per Li atom synthesis. Assuming an efficiency factor β , the ratio of E_{Li} , the total energy needed for Li synthesis, to L_{t} , the total stellar energy from hydrogen burning, is given by

$$\frac{E_{\text{Li}}}{L_{\text{t}}} = \frac{1.6 \times 10^{-7}}{\beta} ,$$

which appears quite possible, but the authors do not postulate a mechanism for actually bringing about the nucleosynthesis.

They also make a calculation for a spallation origin of Li due to cosmic rays striking stationary heavy nuclei in the

atmosphere of a proto-star. The assumptions are: the cosmic ray spectrum for protons is a delta function in proton energy with $E_p = 1$ BeV; a target nucleus of atomic weight A , abundance N_A , will have a spallation cross-section of $A^{2/3}$ in millibarns; the efficiency α_A for producing Li per interaction is linear between $A=12$ and $A=20$ with $\alpha_A=0.1$ for $A=12$ and $\alpha_A=1$ for $A \geq 20$.

The authors obtain the ratio

$$\frac{\text{Li}}{\text{H}} = \frac{U_{\text{cr}}}{E_p} \left[\frac{\sum_{A=12}^{56} N_A \alpha_A A^{2/3}}{N_H^2} \right],$$

where U_{cr} is the cosmic ray energy density at the surface of the star as it condenses. The term in brackets is estimated to be 4×10^{-3} . For $U_{\text{cr}} = 1 \text{ ev/cm}^2$ and $E_p = 10^9 \text{ ev}$ they then obtain $\text{Li}/\text{H} = 4 \times 10^{-12}$. This is low compared to 10^{-9} .

The authors then point out that the observed Li abundance in a star can be up to $M/\Delta M$ of the net abundance in the star, where ΔM is the optically accessible mass of the star and M is its total mass. This enrichment factor would imply that the spallation process is due to a surface phenomenon, concentrating cosmic ray or magnetic field energy at the surface of a forming star. The authors claim trapped magnetic field could supply the energy to produce the observed Li abundance in T-Tauri stars, provided the energy is dissipated near the stars' surface so $\Delta M/M$ is sufficiently small, where ΔM now stands for the mass in the active region of the star. In a volume of space containing one solar mass of gas and initial magnetic field H the total magnetic energy stored is estimated at $5 \times 10^{55} H^2$ ergs. Assuming 250 BeV are needed

to create one Li nucleus (from the cosmic ray result cited above) the observed abundance ratio becomes $\text{Li}/\text{H} = .1\text{H}^2\text{M}/\Delta\text{M}$. Thus for an interstellar magnetic field of $\text{H} = 1 \times 10^{-5}$ gauss and $\Delta\text{M}/\text{M} = 10^{-2}$; $\text{Li}/\text{H} = 10^{-9}$ can be achieved.

Following the paper by Bonsack and Greenstein (BG 60), T. Gold (G 60) pointed out that the surrounding nebulae of T-Tauri stars could be gas remaining after star formation. Spallation reactions in the surface at an early age of the star (during strong magnetic activity) could then create Li in a surface shell of the star. This could then be tied in with a theory of the origin of the solar system in which the shell is thrown off and most of the angular momentum of the sun is transferred to it possibly by magnetic coupling. The high lithium abundance in the earth and meteorites could thus be explained.

In S. Bashkin and D. C. Peaslee (BP 61) the authors come to the following conclusion with regard to light element production: "L nuclei (Li, Be, and B) are produced by spallation, most abundantly during the contraction stages of a forming star. This qualitatively accounts for L abundances in the solar system and T-Tauri stars. For the present sun it is uncertain whether the L nuclei observed are currently produced by flares or are the remains of an original stock."

The paper attempts an abundance calculation:

Consider $p(F)dF = aVe^{-aF}dF$

where $p(F)dF$ is the number of flares per second containing between F and $F+dF$ fast protons ($E_p \geq \sim 70$ MeV), V is the

total rate of flare occurrence in the sun, and a is a parameter specifying the distribution of sizes.

$$V \approx 0.8 \times 10^{-4} / \text{sec},$$

The rate of flares of size F_0 or larger is $P(F_0) = Ve^{-aF_0}$.

For $F_0 \approx 10^{33}$, $P(F_0) \approx 0.5/\text{year}$; hence, $a \approx 8.5 \times 10^{-33}$.

The authors then point out that half of the protons in a flare will go into the sun's surface where they will cause spallation reactions or, more likely, will be stopped by protons. From the p-p cross-section for $E_p = 0.1 - 0.3$ BeV they obtain a mean free path of 6×10^{25} protons/cm². Given a target nucleus, of abundance f relative to hydrogen which has a cross-section for producing particle x of $\sigma(x)$ mb for fast protons, its probability of yielding a particle x per fast proton is $0.06 f\sigma(x)$. The production rate for a particular spallation product is then $Y(x) = 6 \times 10^{26} f\sigma(x)/\text{sec}$ where the total proton flux per second is given by

$$\int_{F=0}^{\infty} P(F)F dF = \int aVe^{-aF}F dF = \frac{V}{a}.$$

For the more numerous protons in the range 10-70 MeV the corresponding rate is $Y'(x) = 2 \times 10^{28} f\sigma'(x)$ where account has been taken of the shorter mean free path of protons in this energy range. The authors then present a more or less quantitative technique which results in an estimate of 80 mb for light-isotope (L) production for the (C,N,O,Ne) targets; with $f = 0.002$ this leads to $Y(L) \approx 10^{26}/\text{sec}$. The authors then show that this production rate is too low to account for even solar abundances:

$$f(L) = \frac{Y(L)T}{N_H} \approx 3 \times 10^{-13}$$

where $f(L)$ is the abundance with respect to hydrogen in the convective envelope of the sun; $T = 1.5 \times 10^{17}$ sec is the age of the sun, and $N_H = 5 \times 10^{55}$ is the number of H atoms in the convective zone. They claim the observed L abundance in the sun is about 10^3 greater than this.

It is also pointed out that the ratio $\frac{Be}{Li} \approx 30$ as observed in the sun is difficult to understand, claiming preferential loss of Li in photosphere or convective zone is not expected.

The series of papers: Fowler, Greenstein, and Hoyle (FGH 61); Fowler, Greenstein, and Hoyle (FGH 62); Burnett, Fowler, and Hoyle (BFH 65); concerns itself specifically with an elaborate theory on the production of the light elements in the spirit of the suggestion by Gold (1960). Mitler (1964) also made detailed calculations based on this model.

The assumptions of the model are: planetary formation has progressed to the point where solid bodies appear in the gaseous disk surrounding the sun. Their composition is $\sim 3/4$ ice, $\sim 1/4$ silicates and perhaps 5% carbon. A proton flux with $\bar{E} \approx 500$ MeV impinges on the material in the disk. In the absence of experimental production cross-sections of the light elements from spallation of O, and Si, the authors assumed production ratios ${}^7\text{Li}/{}^6\text{Li} = 1$ and inferred from the model that ${}^{11}\text{B}/{}^{10}\text{B} = .3$. The proton flux, besides causing spallation of the target elements to form Li, Be, B, also gives rise to a neutron flux which is

thermalized by the hydrogen present. The thermalized neutrons then deplete ${}^6\text{Li}$ and ${}^{10}\text{B}$ to yield the observed terrestrial isotopic ratios ${}^7\text{Li}/{}^6\text{Li} = 12.5$ and ${}^{11}\text{B}/{}^{10}\text{B} = 4$. To estimate the energy needed to form the L nuclei in terrestrial planets, the authors assume one L nucleus is formed in nine proton reactions. Assuming $\bar{E}_p = 500$ MeV they require [4.5 GeV/L nucleus produced]. Assuming [50 L nuclei/ 10^6 Si] were produced by spallation, and taking 4.6×10^{49} Si nuclei present in terrestrial planets, implies 1.7×10^{43} ergs is required. They then consider an estimate by Hoyle according to which 5×10^{45} ergs have to be dissipated in the transfer of the angular momentum of the sun to the planets. If 4% of the energy appears as high energy particles, they find only 10% of the protons need to interact to produce the L nuclei. At present the weakest point of the theory is the ${}^{11}\text{B}/{}^{10}\text{B}$ ratio. Based on the presently known cross-sections for ${}^{11}\text{B}$ and ${}^{10}\text{B}$ production from ${}^{12}\text{C}$ and ${}^{16}\text{O}$, and assuming the contribution of Si spallation does not greatly affect the net production, the ${}^{11}\text{B}/{}^{10}\text{B}$ spallation ratio is 2 for 500 MeV protons. If lower energy protons are considered this ratio can be greater than 4. Hence the depletion of ${}^{10}\text{B}$ by neutrons only increases this ratio above the terrestrially observed value.

6.3 Current Theories of Nucleosynthesis of LiBeB

Ideas present in the early theories combined with new data resulted in a number of elaborate papers. The theories

proposed for light element production are quite distinct.

R. Bernas, E. Gradsztajn, H. Reeves, and E. Schatzman (BGRS 67) attempt to identify the Li, Be, B production site and mechanism as proton spallation of C, N, O, Ne in the solar atmosphere before the Hayashi (fully convective) phase of the sun. The ${}^7\text{Li}/{}^6\text{Li}$ ratio is then changed by ${}^6\text{Li}(p, \alpha)$ reactions at temperatures between 2 and 4 million degrees at the bottom of the surface convective zone during the Hayashi phase. The material forming the planetary system would still later have separated from the sun.

A number of spallation production cross-sections with 150-MeV protons on ${}^{12}\text{C}$ and ${}^{16}\text{O}$ had been measured by these authors. They supplemented these with estimates based on isospin formalism or with calculations based on the Serber statistical method. Thus starting with a complete set of cross-section values and a probable target mixture they could calculate the formation rate of the light isotopes from

$$\frac{dn_L}{dt} = \sum_M n_M \int_{Q_{M,L}} \sigma(M, L) \phi(E_p) dE_p \quad 6.31$$

where n_L is the density of isotope L produced (nuclei/cm³),

n_M is the density of target isotope M (nuclei/cm³),

$\sigma(M, L)$ is the cross-section for producing L from M by protons of energy E_p ,

$Q_{M,L}$ is the threshold proton energy for producing nucleus L from target M,

and $\phi(E_p)$ is the proton flux.

The authors use $n_C/n_H = 3 \times 10^{-3}$, $n_N/n_H = 10^{-4}$, $n_O/n_H = 10^{-3}$, $n_{Ne}/n_H = 3 \times 10^{-3}$ for the isotopic target composition. They consider a probable average proton energy spectrum as observed in solar flares and calculate isotopic spallation ratios ${}^7\text{Li}/{}^6\text{Li} = 2.5 \pm 1.0$ and ${}^{11}\text{B}/{}^{10}\text{B} = 5 \pm 2.5$. They compare these with the terrestrial-meteoritic values and find that the ${}^{11}\text{B}/{}^{10}\text{B}$ ratio requires no depletion mechanism while the ${}^7\text{Li}/{}^6\text{Li}$ spallation ratio must be modified by the mechanism outlined above. Of the light elements the energy requirement for Be production is largest.

For stellar production the time integral of equation 6.31 yields for the production of the light nucleus L

$$\frac{n_L}{n_H} \leq \int \phi_p(t) \sigma(L) (n_{CNO}/n_H) X(t) dt \quad 6.32$$

where $X(t) = M_i/M_c$ is a dilution factor; M_i is the mass in which the spallation process occurs; M_c is the total mass of the convective zone on which M_i can be mixed. The possibility of burn up at the bottom of the convective zone is allowed for by the $<$ sign. From the estimated average spallation cross-sections leading to Be of 2 mb and the abundance of Be in the sun the integral equation becomes

$$\int \phi_p(E > 40 \text{ MeV}) X(t) dt \approx 10^{20} / \text{cm}^2.$$

For the present sun the authors estimate $X(t) \approx 10^{-8}$ and the proton flux capable of spallation is $\phi_p(t) = 10^7 / \text{cm}^2 \text{ sec}$. Assuming the age of the sun is 5×10^9 years, the integral yields 1.6×10^{16} . The authors place the limits 7×10^{15}

$< \int \phi_p X dt < 7 \times 10^{16}$, and find the activity is too low by about 10^3 . In the case of T-Tauri stars the authors estimate the convective mass is 0.1 of the total mass hence $X(t) = 10^{-11}$; the period of the phase $\approx 10^{6.5}$ years, so to yield $\int \phi_p X dt = 10^{20}$ the particle flux must be $\approx 10^{16}$ protons/cm²/sec or 10^{42} erg/year. For a star the size of the sun, this is a very large energy requirement. The authors then point out that the Herbig-Haro phase of a star, before it becomes luminous, might also be the production site.

To estimate the production of light elements in galactic cosmic rays the authors considered a proton flux above 100 MeV of about 2 particles/cm²/sec. The ratio $n_{\text{CNO}}/n_{\text{H}} = 3 \times 10^{-4}$ is taken as a time average over the age of the galaxy (10^{10} years).

$$\frac{n_{\text{L}}}{n_{\text{H}}} = \int \phi_p (n_{\text{CNO}}/n_{\text{H}}) \sigma_{\text{L}} dt$$

for $\sigma_{\text{L}} \approx 30$ mb this yields $n_{\text{LiBeB}}/n_{\text{H}} \approx 1.6 \times 10^{-11}$, while 10^{-9} is found in several stars, the meteorites, and the earth.

H. E. Mitler (MI 67) wrote a critical review of theories on the origin of the rare light nuclides. In particular he made calculations on the energy requirement for producing cosmic abundances by proton spallation of CNO on the surface of stars and compared the total energy to the energy available from gravitational contraction. This is of interest for the T-Tauri phase and the Herbig-Haro phase as considered in the Bernas et al. model. The ratio is ≈ 300 for the Herbig-Haro phase hence eliminating it from consideration. For the T-Tauri phase the ratio is 2 for the Bernas et al. model.

These calculations are based on the Be abundance in the sun, which represents the most severe energy requirement. Similar calculations based on our measured cross-sections yield almost identical results.

Mitler considers that the accelerating distance for a proton may be ~ 4 times its stopping distance, hence the irradiated material could be about 5 times as great as considered by Bernas, yielding a ratio of $E_{\text{spal}}/E_{\text{grav}} = 0.4$; this puts the T-Tauri phase in the energetically just possible range. Mitler then proposes an alternate theory where most of the lithium (${}^7\text{Li}$) is made in a big bang and the remaining light isotopes are produced by spallation during the T-Tauri phase. No burn up of ${}^6\text{Li}$ and hence no mixing in a convective zone before ejection is required in this model. The energy requirement then decreases by over a factor of 100, making the process energetically quite possible.

The difficulties encountered in theories of autogenetic origin of light elements in stars led H. Reeves, W. A. Fowler, and F. Hoyle (RFH 70) to a theory which attempted to show that the light elements were produced by galactic cosmic rays. They divided the energy range of galactic cosmic rays into three regions; $E < 5$ MeV/nucleon, $5 < E < 30$ MeV/nucleon, and $E > 30$ MeV/nucleon. They then considered the contribution of $p+C$, N , O ; $\alpha+C$, N , O ; p , $\alpha+\text{Mg}$, Si , Fe ; and $\alpha+\alpha$ in the middle and high energy region, where they assigned likely mean cross-sections for the various production mechanisms.

For the case of spallation of heavy fast particles on residual gas the escape from the galactic disk and the nuclear destruction of the light elements produced were taken into consideration.

The generation rate of lithium per H atom was found to be $\frac{d}{dt} \left(\frac{\text{Li}}{\text{H}} \right) \approx 7 \times 10^{-28} \text{ sec}^{-1}$. To achieve a lithium abundance of $\frac{\text{Li}}{\text{H}} \sim 10^{-9}$ a total time integrated flux of $5 \times 10^{18} \text{ particles/cm}^2$ is needed. For a galactic age of 1.2×10^{10} years this represents an average flux of $12 \text{ particles/cm}^2 \text{ sec}$ instead of the present flux of $3.6 \text{ particles/cm}^2 \text{ sec}$.

It is instructive to compare this calculation with the estimate in the paper by Bernas et al. (BGRS 67), which found the discrepancy to be a factor of 170.

Bernas et al.

Reeves et al.

protons $> 100 \text{ MeV} \sim 2 / \text{cm}^2 \text{ sec}$

protons $> 30 \text{ MeV} \sim 3.6 / \text{cm}^2 \text{ sec}$

$n_{\text{CNO}} / n_{\text{H}} = 3 \times 10^{-4}$

$n_{\text{CNO}} / n_{\text{H}} = 15 \times 10^{-4}$

time $\sim 10^{10} \text{ years}$

time $\sim 1.2 \times 10^{10} \text{ years}$

$\sigma_{\text{Li}} \sim 30 \text{ mb}$

$\sigma_{\text{Li}} \sim 30 \text{ mb}$

4.5
enhancement
factor

+ equal production from heavy
cosmic ray spallation.
+ 1/2 production from α
spallation.
+ 2x production from α - α .

All together this yields a factor of 50. Thus some new data, a new production mechanism plus some bias on either side can make a significant change in the evaluation of a theory.

Better data especially in the low energy region of cosmic rays and solar flares, as well as for abundance measurements of light and medium heavy nuclei may very well lead to revised theories.

From the low threshold of $^{14}\text{N} + \text{p} \rightarrow ^{11}\text{C} \rightarrow ^{11}\text{B}$ and the solar system ratio of $^{11}\text{B}/^{10}\text{B}$, the authors find that the contribution to ^{11}B from the flux in the medium energy region is low, and imply the flux at protons in the $5 < E < 30$ MeV range is $\leq 5/\text{cm}^2\text{sec}$. The observed terrestrial abundance of deuterium cannot be accounted for by galactic cosmic rays. The authors suggested big bang nucleosynthesis or neutron capture in the atmosphere of neutron stars.

H. E. Mitler (MI 70) gave a detailed calculation of light element production in galactic cosmic rays, using then available cross-sections for ^{12}C and ^{16}O and estimates for $\alpha + \alpha$ reactions. He made a more or less arbitrary extrapolation of the cosmic ray flux below 100 MeV/nucleon for his calculations. The abundances obtained by Mitler, assuming the galaxy is unchanged since its birth, were extremely close to those observed in meteorites (Be and B especially). It should be pointed out that absolute abundances are very uncertain, values obtained for the crust of the earth, for example, are about ten times higher than those obtained for chondritic meteorites. Mitler then allowed for higher production in the primitive galaxy as well as processing of galactic material and found that at the time of solar genesis the abundances of the first calculation would be increased

by a factor of 2.5. He concluded that he could not make sufficient ${}^7\text{Li}$ in galactic cosmic rays and suggests cosmological production as in Mitler (MI 67). There is also difficulty with the ${}^{11}\text{B}/{}^{10}\text{B}$ ratio (too low) as well as with low isotopic ratios ${}^7\text{Li}/{}^6\text{Li}$ observed in stars. Mitler lists the usual palliatives plus the possibility of a neighborhood supernova supplying thermonuclear lithium.

One additional observational aspect should be mentioned because it has bearing on the question of light element production in stars. Herbig (HE 65) pointed out an interesting correlation of Li abundance and stellar age. Young stars seem to have more lithium than older stars; the usual explanation is that a slow destruction mechanism such as (p,α) reactions at the bottom of a convective zone is operative. ${}^7\text{Li}/{}^6\text{Li}$ ratios are known for many stars and vary from 2 to greater than 20. The lower ratio is assumed to be the spallation ratio which will tend to increase during depletion since the ${}^6\text{Li}(p,\alpha)$ rate is faster than the ${}^7\text{Li}(p,\alpha)$ rate at the temperatures estimated. However at present there is no correlation between high ${}^7\text{Li}/{}^6\text{Li}$ ratios and stellar age. A good summary of light element observations in stars is given by I.J. Danziger (DA 67).

Cosmological production of the light elements has also been investigated and may possibly account for ${}^7\text{Li}$ production as calculated by R. V. Wagoner, W. A. Fowler, and F. Hoyle (WFH 67). In a calculation for nucleosynthesis in exploding objects (little bangs) R. Wagoner (WA 69) finds that ${}^7\text{Li}$

and ^9Be production would exceed and dominate the spallation contributions as estimated in (BGRS 67), while ^6Li and B would be due to spallation production.

7. IMPACT OF NEW CROSS-SECTIONS

7.1 Introduction

Our cross-section measurements are particularly valuable for model calculations of the type proposed in (BGRS 67). The most significant calculations are based on the precise isotopic ratios ${}^7\text{Li}/{}^6\text{Li}$ and ${}^{11}\text{B}/{}^{10}\text{B}$. Net abundances are much more difficult to measure since chemical weathering does separate elements but has no effect on the isotopic composition of a particular element. It was found that the ratio ${}^7\text{Li}/{}^6\text{Li} = 12.5$ holds for chondritic meteorites and for rock samples of the earth (KM 64). Similarly the ratio ${}^{11}\text{B}/{}^{10}\text{B} = 4.0$ holds for meteorite (SH 63) and earth rock samples (RA 63).

7.2 Isotopic Ratio Calculations

To calculate these ratios we consider the following model for proton spallation in stellar atmosphere type environments:

- 1) target mixture: ${}^{12}\text{C}:{}^{14}\text{N}:{}^{16}\text{O} = 3:1:5$ [This holds for solar cosmic rays according to E.A. Muller (Mu 68).]
- 2) proton flux with spectrum $E^{-\gamma}$ [Solar flares usually fit this (FW 65).]

The relative production of a particular isotope is then given by:

$$I_i = \sum_j \int_{E_0}^{\infty} \sigma_{ji}(E) E^{-\gamma} X_j dE, \quad 7.21$$

σ_{ji} is the cross-section for producing isotope i from target j ,

x_j is the weighing factor for target j as given above,

E_0 is the threshold energy of $\sigma_{ji} \neq 0$.

To perform the integration we supplement the cross-section measurements performed at this lab with other available data summarized in Table 14. A linear interpolation between data points is used. This is the cause of the kinked curved lines in the logarithmic graphs of Figure 18 where all the $\sigma_{ji}(E)$ used in the integration are shown. Cases of conflicting data were resolved as follows: the last published values by the same authors were preferred over earlier data; emulsion data was given least credence; final data were preferred over preliminary data. The high energy region (>200 MeV) of mass 10 from ^{12}C was based on the cross-section for ^{10}C at 1 GeV, which was doubled to account for ^{10}B . The high energy region (>42 MeV) for mass 11 from ^{14}N is based on ^{11}C cross-sections only; no correction was attempted since the cross-section for mass 11 measured at 42 MeV was comparable to ^{11}C cross-sections at higher proton energy and other spallation cross-section curves tend to slowly decrease towards higher energy. Where data were available at closely spaced points (ES 71), representative points were plotted.

We then calculated the ratios I_7/I_6 and I_{11}/I_{10} for $1.25 \leq \gamma \leq 5.25$. For $\gamma \leq 2$ there must be an energy cutoff $E_{\text{max}} < \infty$ since otherwise the average proton energy is not finite. In the calculation for I_j this is not critical however; the value $E_{\text{max}} = 30$ GeV is taken for all integrations. For a constant cross-section of σ , $\gamma = 1.25$, and $E_0 = 10$ MeV,

Table 14. Spallation Data for ^{12}C , ^{14}N and ^{16}O Targets.

Cross-Sections in mb.					
Source	E_p	Target	Mass 6	Mass 7	Mass 9 Mass 10 Mass 11
GR 65	50	^{12}C	9.2	32.7	
GR 65	155	^{12}C	9.8	19.9	
GR 65	550	^{12}C	7.4	16.6	
AER 67	50	^{12}C			^{11}C 86.4
AER 67	150	^{12}C			>8.6 61
JU 70	125	^{12}C	8.3		
AER 67	980	^{12}C			^{10}C 3.3
AER 69	3 GeV	^{12}C	8.3	18.7	
FPLYB 71	150	^{12}C			3.2
FPLYB 71	600	^{12}C			5.3
JU 70	125	^{14}N	12.7	11.1	
AER 69	3000	^{14}N		^7Be 12	
AER 67	156	^{14}N			^{11}C 15
AER 67	522	^{14}N			^{11}C 22
AER 67	980	^{14}N			^{11}C 25.5
AER 67	5700	^{14}N		^7Be 8.6	^{11}C 11
ES 71	4.5	^{14}N			10
ES 71	5.5	^{14}N			56
ES 71	6.5	^{14}N			190
ES 71	8.5	^{14}N			220
ES 71	10.5	^{14}N		0.3	180
ES 71	14.5	^{14}N		5.6	140
BCJR 71	14	^{14}N			190

Table 14. (continued)

Source	E_p	Target	Mass 6	Mass 7	Mass 9	Mass 10	Mass 11
YBDFGB 68	135	^{16}O	10.	13.4	1.7	11	25
GR 65	155	^{16}O	9.8	19	1.7		
AER 67	155	^{16}O		13		11	25
YI 68	600	^{16}O	12.4	19.3	2.6	12	25
YI 68	19000	^{16}O	14.4	25.0	3.6	15	<45

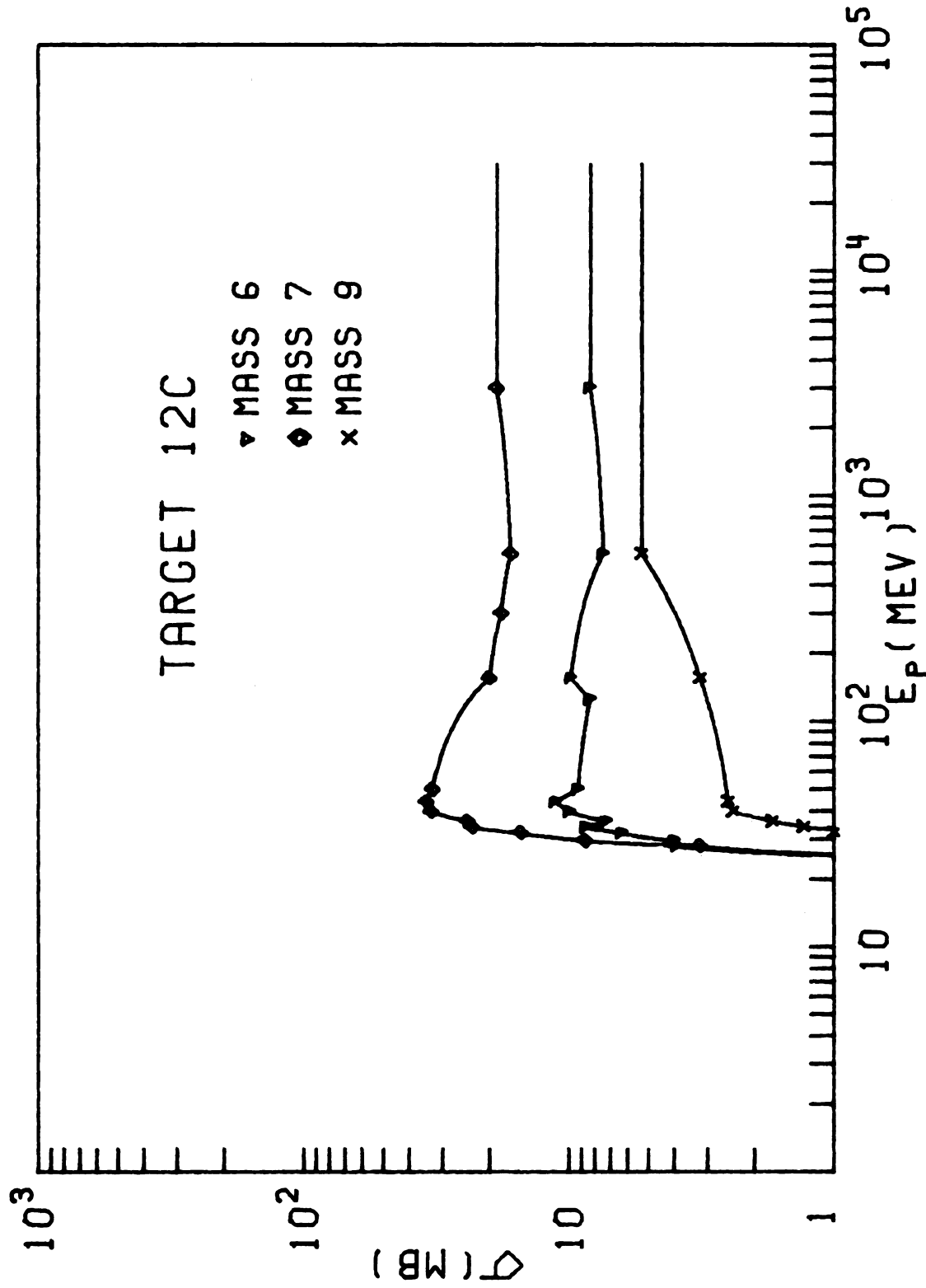


Figure 18. Total Cross-Sections as a Function of Proton Energy for Spallation Products Mass 6 to Mass 11 from Targets ^{12}C , ^{14}N and ^{16}O .

Figure 18. (continued)

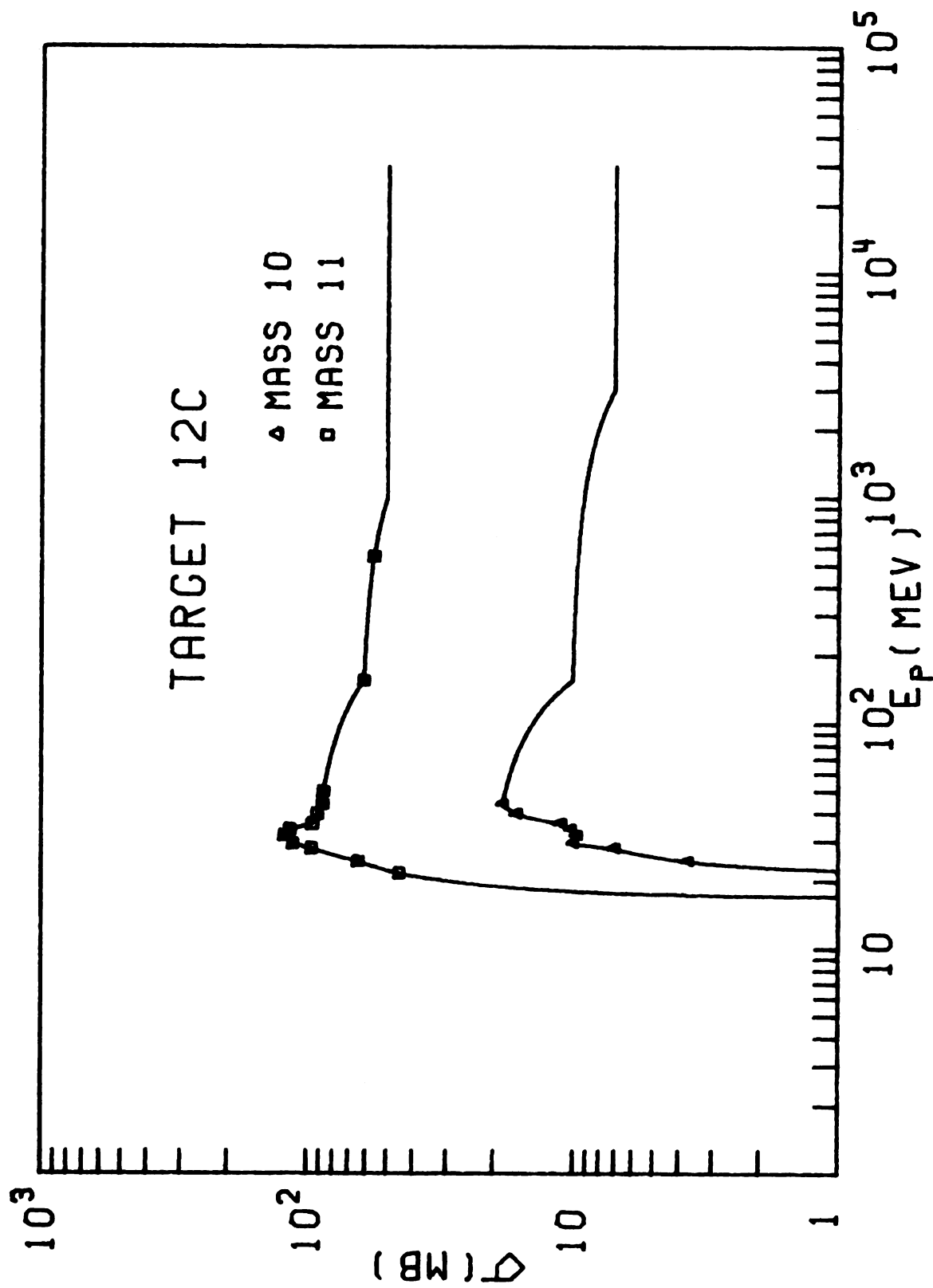


Figure 18. (continued)

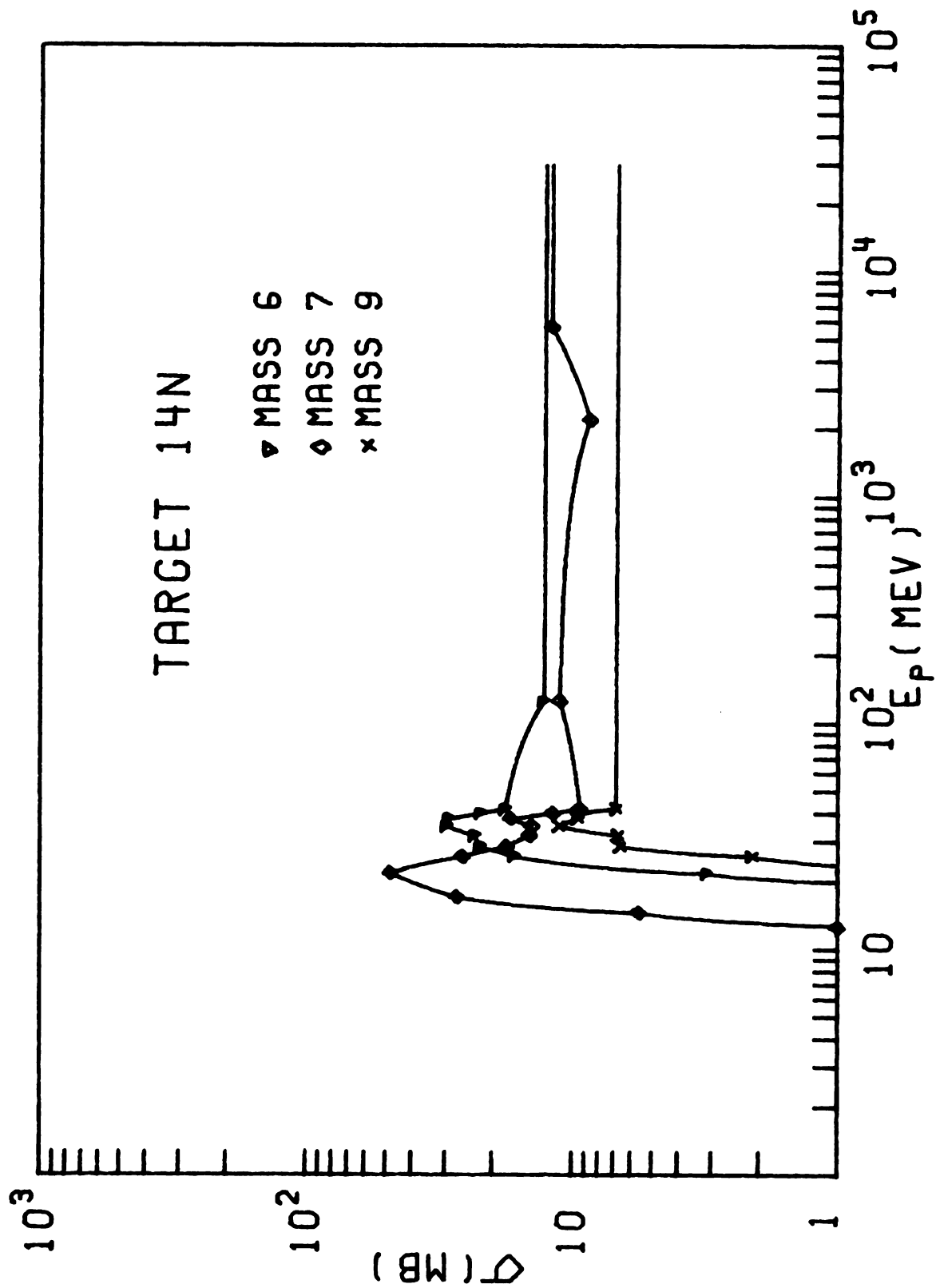


Figure 18. (continued)

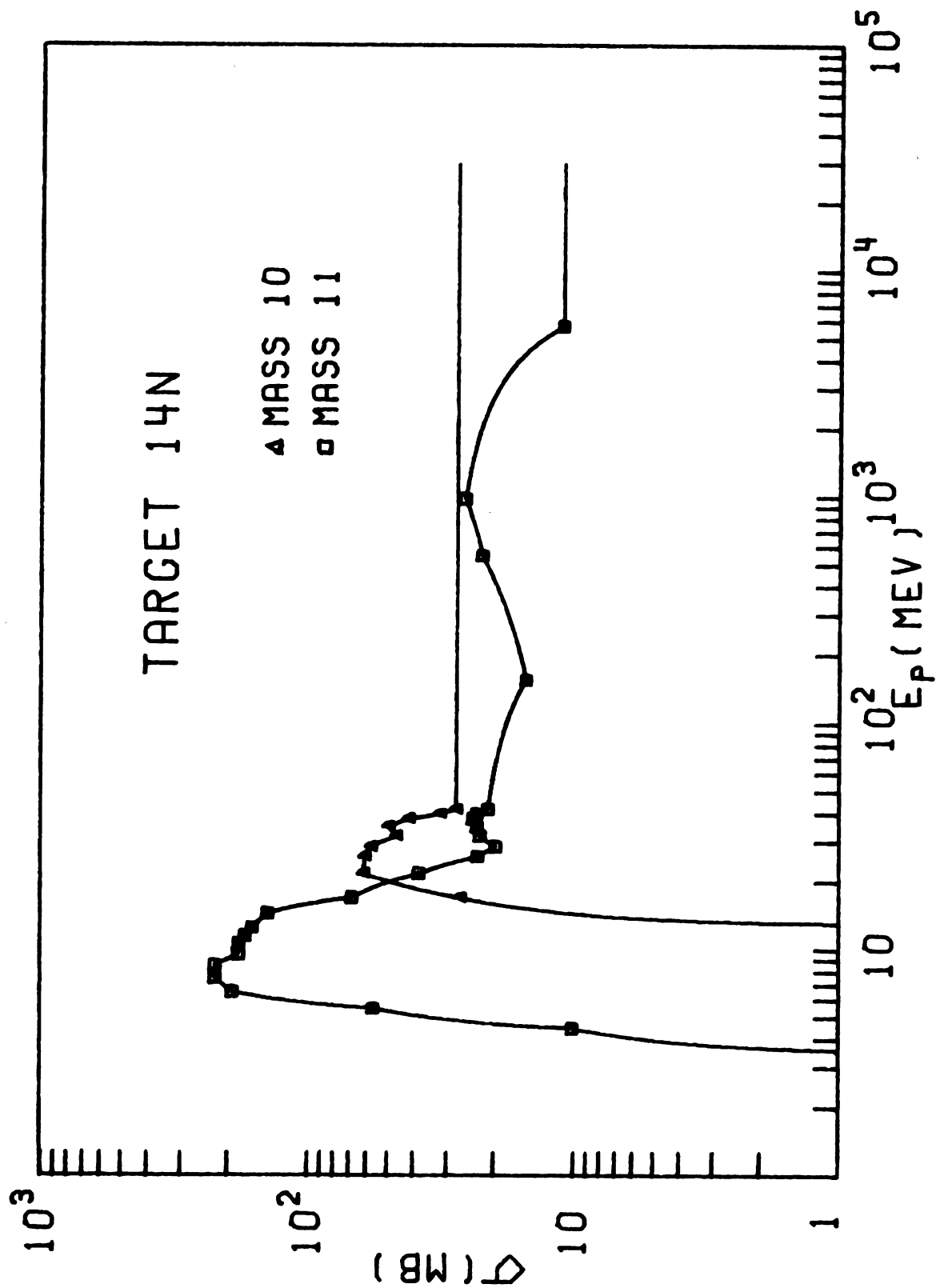


Figure 18. (continued)

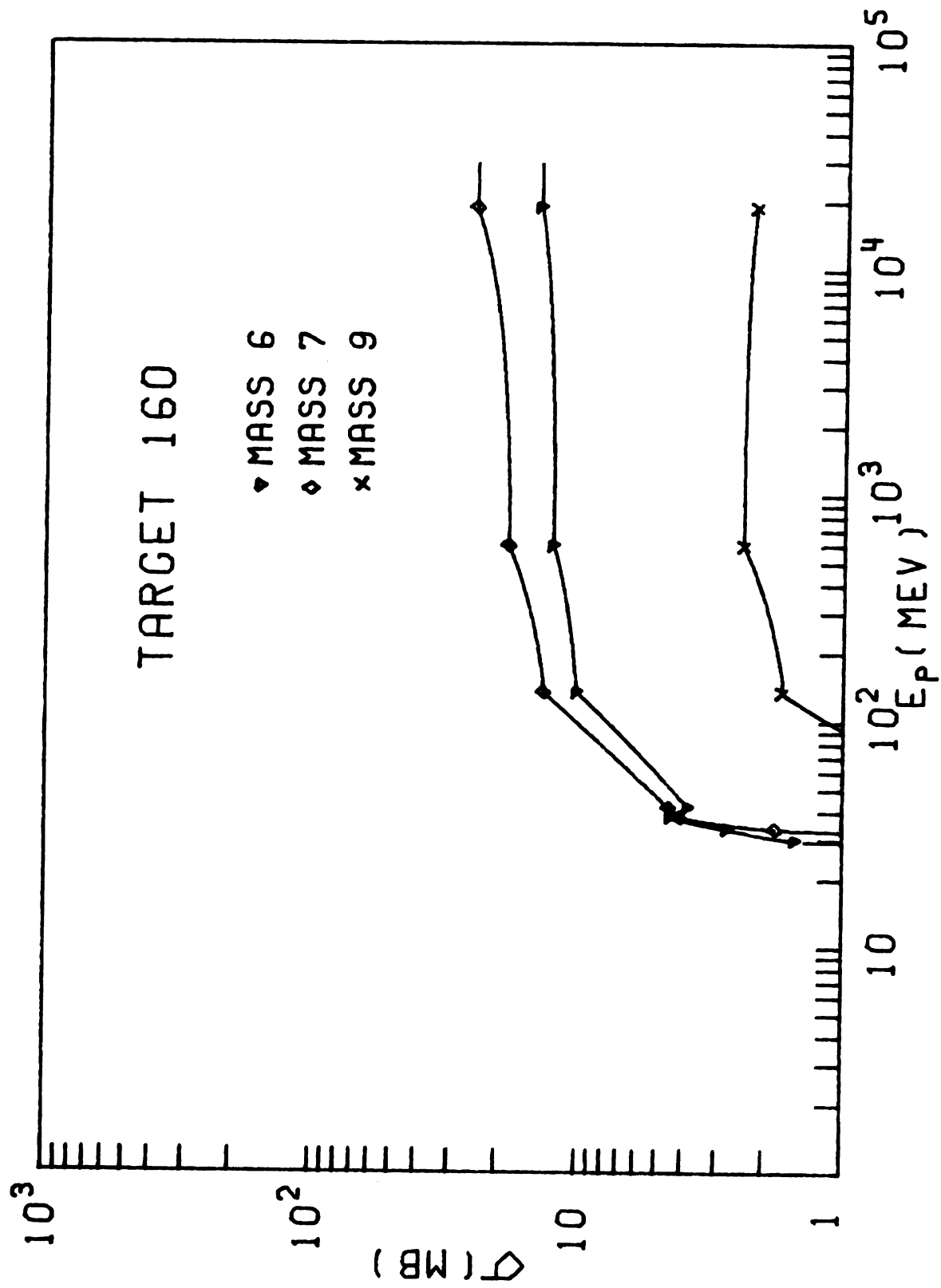
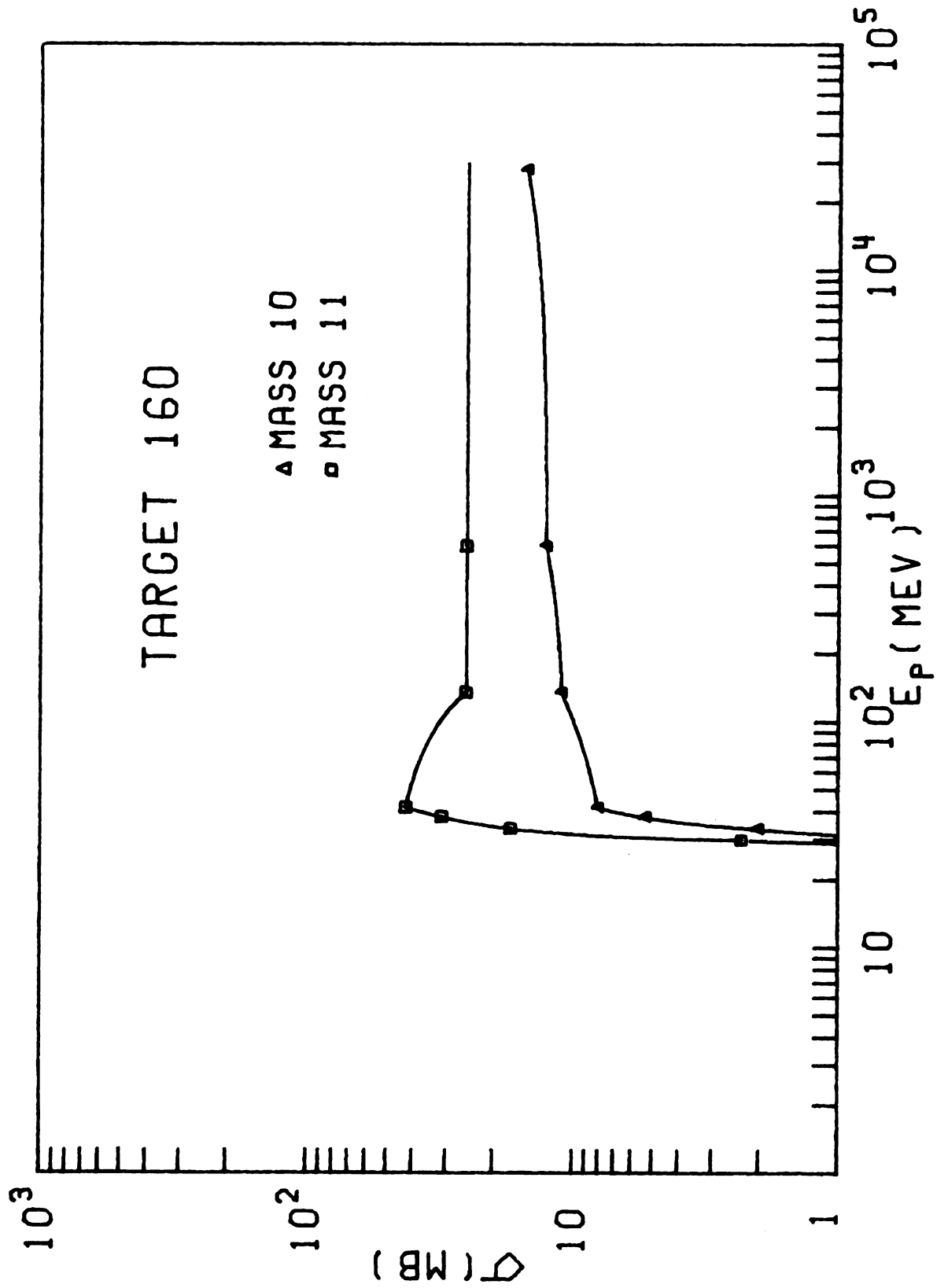


Figure 18. (continued)



$I_j(E_{\max}=30 \text{ GeV})/I_j(E_{\max}=\infty) = 0.96$; for $\gamma = 1.50$ the ratio is already 0.998. When no cross-section measurements are available at this energy, the cross-section at the nearest lower energy is assumed to be constant out to E_{\max} . Figure 19 shows a bar graph which exhibits the net contribution to isotope j by the different targets for two values of γ . It is evident that ^{14}N is the most important target in this model in spite of its lower abundance.

Figure 20 and Table 15 summarize the calculated ratios. Comparing the observed isotopic ratios $^7\text{Li}/^6\text{Li} = 12.5$ and $^{11}\text{B}/^{10}\text{B} = 4.0$ to these values, one finds that the boron ratio is matched only for γ close to 1.25 and then increases rapidly with increasing γ , while the Li ratio is near 2 for low values of γ and even for $\gamma = 5.25$ it only reaches the value 6. There is hence no hope of attaining both observed ratios with a proton spectrum of the proposed form and a specific γ . From Figure 10 for ^{14}N cross-sections it is evident that a special proton spectrum, peaked below 30 MeV but not rising as a high power of E to 10 MeV, can reproduce the observed ratios (this type of argument was already proposed in Bernas et al. (BGRS 67)). That this represents a physical situation is not at all clear however. More likely is some type of preferential depletion mechanism for ^6Li or also cosmological ^7Li production. Even the boron ratio is not really satisfactory. Solar flares with $\gamma \sim 3$ are what is actually observed. We get a ratio of

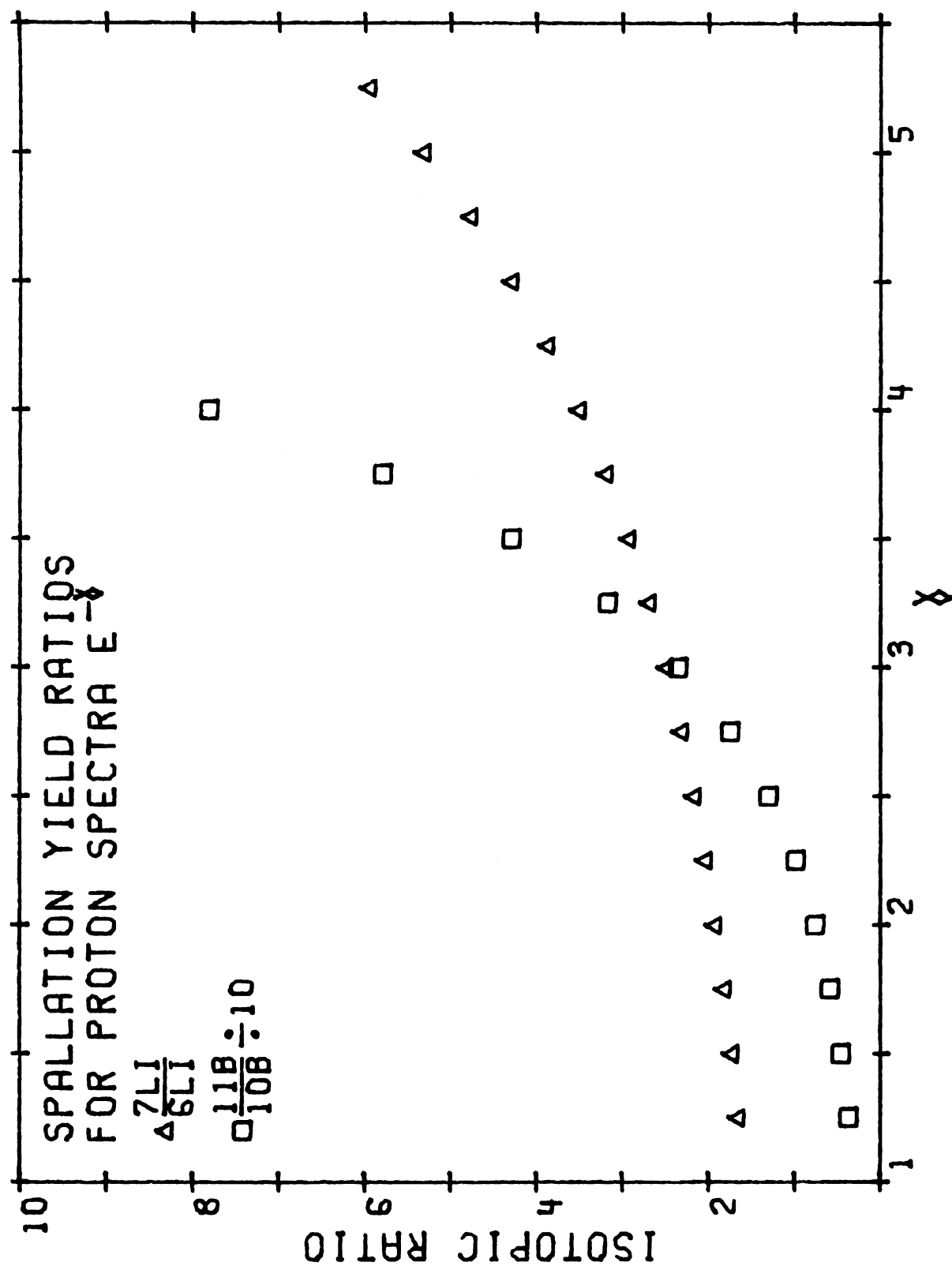


Figure 20. Isotopic Spallation Ratios as a Function of Proton Spectra.

Table 15. Isotopic and Elemental Spallation Production Ratios
 From a Target Mixture C:N:O (3:1:5) by Proton
 Spectra $E^{-\gamma}$.

γ	$7\text{Li}/6\text{Li}$	$11\text{B}/10\text{B}$	Li/Be	B/Be	B/Li
1.25	1.7	3.7	9.2	22.8	2.5
1.50	1.8	4.6	10.0	32.4	3.2
1.75	1.8	5.8	11.0	47.2	4.3
2.00	1.9	7.5	12.1	69.1	5.7
2.25	2.1	9.8	13.2	101.7	7.7
2.50	2.2	13.0	14.3	150.9	10.6
2.75	2.3	17.3	15.4	225.6	14.6
3.00	2.5	23.3	16.7	339.6	20.3
3.25	2.7	31.5	18.2	513.8	28.3
3.50	2.9	42.6	19.8	779.9	39.4
3.75	3.2	57.6	21.6	1186.4	54.8
4.00	3.5	77.8	23.8	1807.2	76.0
4.25	3.9	104.9	26.3	2754.4	104.9
4.50	4.3	141.2	29.1	4199.5	144.2
4.75	4.8	189.8	32.4	6403.6	197.4
5.00	5.3	254.8	36.3	9765.1	269.2
5.25	6.0	341.5	40.7	14893.5	365.8

$^{11}\text{B}/^{10}\text{B} \approx 20$ in that case. Thermal neutrons would increase this ratio (they deplete ^{10}B preferentially), thermal protons decrease it only at a temperature which would lead to complete destruction of Li. Hence a mechanism to alter this ratio is difficult to come by.

Thus far we may draw the following conclusions: While ^{14}N dominates the light element production (especially for $\gamma \geq 3$), we have not obtained results that differ greatly from calculations based on guesses for the ^{14}N cross-sections, indicating these early results were rather fortuitously correct. The $^{11}\text{B}/^{10}\text{B}$ ratio suggests that the proton spectrum causing spallation is rather flatter than what is observed in solar flares.

7.3 Energy Requirement of (BGRS 67) Model

The energy requirement in the (BGRS 67) theory is critical to its validity, we calculate it for the most severe case, the ^9Be abundance in the sun. Starting from equation 6.31 we find after integrating with respect to energy and time that for a time integrated proton flux $\int \phi_p(t) dt \propto E^{-\gamma}$, the minimum areal energy density

$$W(\text{MeV}/\text{cm}^2) \equiv \int_{E_C}^{\infty} \phi(E) E dE$$

required to produce all the ^9Be in the sun is given by (provided $\gamma > 2$):

$$-W = \frac{n_{^9\text{Be}} E_C^{-\gamma+2} M_C}{n_{\text{CNO}} (-\gamma+2) (I_9) M_i}$$

E_C is the low energy cutoff of the proton spectrum and to

obtain a lower limit on W this is chosen close to the ${}^9\text{Be}$ production threshold. The other variables are defined in section 6.3 and 7. For solar abundances from Table 13

and for $\frac{M_i}{M_C} = 2 \times 10^{-8}$ (MI 67):

$$W \approx \frac{10 E_C^{-\gamma+2}}{(\gamma-2) I_9} .$$

For $E_C = 30$ MeV, $\gamma = 3$, equation 7.21 yields $I_9 = \frac{0.11 \times 10^{-29}}{\text{MeV}^2} \text{ cm}^2$; we obtain

$$W = 3 \times 10^{29} \text{ MeV/cm}^2 .$$

For the surface of the sun the total energy required is then 3×10^{46} erg. For $\gamma = 4$, $E_C = 30$ MeV, equation 7.21 yields $I_9 = \frac{0.249 \times 10^{-31}}{\text{MeV}^3} \text{ cm}^2$ so that

$$W = 2.2 \times 10^{29} \text{ MeV/cm}^2 .$$

Both values are close to the estimates in (MI 67) and (BGRS 67).

7.4 Observations

A reliable calculation of the net contribution of various light element production mechanisms is at present not possible. To repeat the calculations by H.E. Mitler (MI 70) without measurements of $(\alpha+\alpha)$ cross-sections or better knowledge of the low energy cosmic ray flux would be premature. The calculations for stellar production depend critically on stellar models since mixing and burnup in convective zones can cause large changes in relative abundances. Cosmological contributions are the most difficult to estimate since very little observational

evidence can be found which is directly related to this mechanism. To all this is added the large uncertainty in the actual net abundance measurements, so even if a calculation is attempted, one does not really know with what one should compare. It would be very interesting to have boron isotopic ratios available from stars. Unlike the range of lithium isotopic ratios observed, from 2 (close to the spallation ratio for low γ) to over 20, which is usually explained by cosmological production or differential depletion, the boron isotopic ratio, apparently not changed by either of these mechanisms, should be the production ratio. Large fluctuation in the ratio are not expected and any such fluctuations would provide better insight into the production mechanism.

APPENDICES

APPENDIX A

IONS TRAVERSING KAPTON

The manufacturer of Kapton does not reveal its exact formula. However from the 21.65 MeV γ -counting experiment it is easily inferred that it is mostly carbon.

By weighing several pieces of 1 mil Kapton an average areal density $3.8 \pm 0.1 \text{ mg/cm}^2$ was found. The stopping powers for protons on ^{12}C as shown in Table 16 are taken from (WBP 66).

Table 16. Proton energy loss in Kapton.

Proton Energy (MeV)	Stopping Power (MeV cm ² /g)	Proton energy loss (MeV) in 0.0005" Kapton
22 MeV	21.4	.081
42 MeV	12.7	.048

For the 21.65 MeV γ -counting experiment it is important to know whether ^7Be and ^{11}C are stopped by the Kapton.

The relations

$$R = R_0 \frac{m}{m_0} \left(\frac{Z_0}{Z} \right)^2$$

and

$$E = E_0 \left(\frac{m}{m_0} \right)$$

make it possible to use (WBP 66) to find the approximate ranges for ^7Be and ^{11}C .

R_0 is the range of the tabulated nucleus;

Z_0 is its charge;

m_0 is its mass;

E_0 is its energy.

R, Z, m , and E are the corresponding variables for the nucleus of interest. In the energy range 1 MeV/nucleon and using ^4He data, these formulas underestimate by a factor of 2 the ^{12}C range in water and aluminum (see SE 68, Figures 25 and 26).

At 21.65 MeV the maximum energy for ^7Be is 9.56 MeV; the maximum energy for ^{11}C is 10.13 MeV. The lab angle is of course 0° with respect to the beam for these cases. To find the range for these particles one first calculates the energy of the α particle given by the energy relation

$$E_{\alpha}^{^7\text{Be}} = (9.56 \text{ MeV}) (4/7) = 5.46 \text{ MeV for } ^7\text{Be}$$

$$E_{\alpha}^{^{11}\text{C}} = (10.13 \text{ MeV}) (4/11) = 3.48 \text{ MeV for } ^{11}\text{C}$$

The range of the α particle in ^{12}C at a calculated energy can now be looked up in (WBP 66).

$$R_{\alpha}^{^7\text{Be}} = 4.7 \times 10^{-3} \text{ g/cm}^2$$

$$R_{\alpha}^{^{11}\text{C}} = 2.4 \times 10^{-3} \text{ g/cm}^2$$

The range can now be calculated using the first equation

$$R^{^7\text{Be}} = (4.7 \times 10^{-3} \text{ g/cm}^2) (7/4) (2/4)^2 = 2.05 \times 10^{-3} \text{ g/cm}^2$$

$$R^{^{11}\text{C}} = (2.4 \times 10^{-3} \text{ g/cm}^2) (11/4) (2/6)^2 = 0.73 \times 10^{-3} \text{ g/cm}^2$$

Since these are underestimates by a factor of 2, it is evident that while 0.0005" Kapton is thick enough to stop the ^{11}C ; 0.001" Kapton is needed to stop all ^7Be .

APPENDIX B

SLIT SYSTEM DESIGN CALCULATIONS

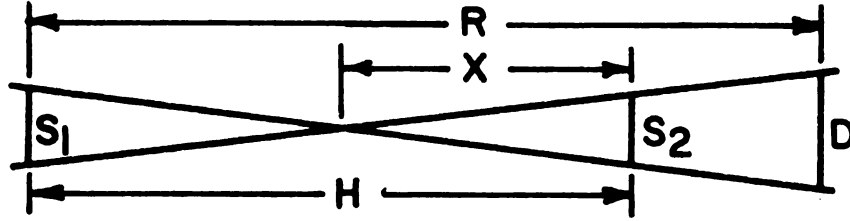


Figure 21. Geometry of Slit System with Beam at 90° .

In Figure 21 S_1 and S_2 represent the back and front slit respectively. D represents the part of the beam trajectory visible to the detector for the beam at 90° to the slit axis. The yield $Y \propto S_1 S_2$ should be maximized for a given D . From Figure 21 the geometrical relationships are evident:

$$\frac{\frac{S_2}{2} + \frac{S_1}{2}}{H} = \frac{\frac{S_2}{2}}{X} = \frac{\frac{D}{2}}{X+R-H}$$

These results then follow:

$$X = H \frac{S_2}{S_2 + S_1}$$

$$D = \left(H \frac{S_2}{S_2 + S_1} + R - H \right) \left(\frac{S_2 + S_1}{H} \right) = \frac{R}{H} S_2 + \frac{(R-H) S_1}{H}$$

To maximize Y set $dY = 0 = S_2 dS_1 + S_1 dS_2$ subject to $D = \text{constant}$

$$\frac{R}{H} + \frac{R-H}{H} \frac{dS_1}{dS_2} = 0$$

$$-dS_2 = \frac{R-H}{R} dS_1$$

$$S_2 dS_1 + S_1 \left(\frac{H-R}{R} dS_1 \right) = 0$$

$$S_2 = S_1 \left(\frac{R-H}{R} \right)$$

The last formula has the following meaning. If $H \sim R$, that is if the front slit is very close to the beam, then the size of the back slit is only limited by the detector size. The choice of the front slit opening is critical for beam trajectories other than 90° . Then the range of possible flight paths depends strongly on both beam width W and front slit width S_2 . This is shown in Figure 22.

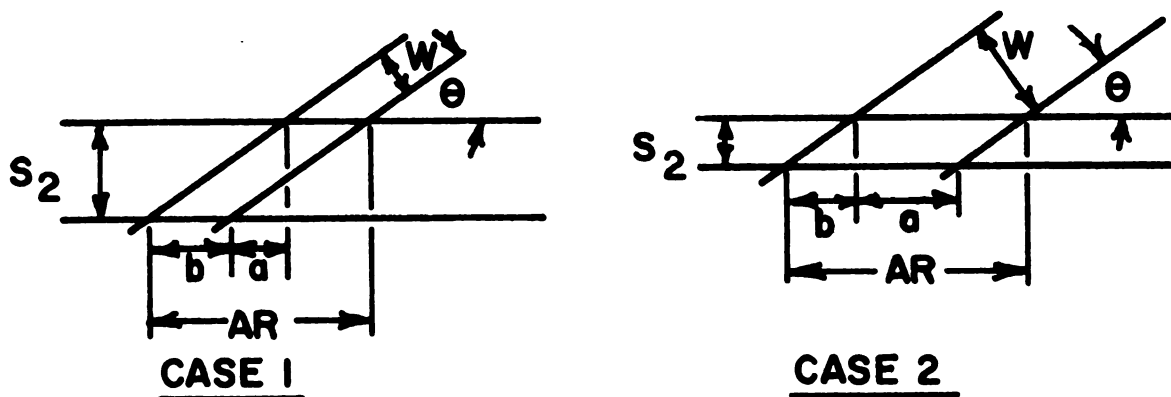


Figure 22. Approximate Range of Path Length Differences. AR is the approximate range of path lengths. From Figure 22 it is seen that $AR = a + 2b$.

$$\text{case 1: } a+b = \frac{S_2}{\tan\theta} \quad b = \frac{W}{\sin\theta} \quad (S_2 > W)$$

$$\text{case 2: } a+b = \frac{W}{\sin\theta} \quad b = \frac{S_2}{\tan\theta} \quad (W > S_2)$$

$$AR = \frac{W}{\sin\theta} + \frac{S_2}{\tan\theta} \quad \text{for both cases.}$$

This shows that for small angles θ , the beam spot size and front slit width are equally critical as far as timing resolution is concerned. Yield $Y \propto WS_2$. This is so because

in making the beam spot small, the beam intensity is cut down proportionally. It is thus of advantage to have $W \approx S_2$. This maximizes yield for constant timing resolution for small θ . Near $\theta = 90^\circ$, $AP \approx W$ and the front slit width is not critical.

APPENDIX C

FORMVAR FILM THICKNESS MEASUREMENT

The stopping power for a compound can be calculated from the stopping power of constituent elements using the formula.

$$\text{STOPPING POWER} = \frac{dE}{d(\rho_C x)} = \sum_E \frac{dE}{d(\rho_E x)} \frac{\rho_C}{(\rho_E)} \quad (1)$$

ρ_C is the density of the compound

ρ_E is the density of an element

ρx is the areal density.

The formula of formvar is $H_{16}C_8O_4$ so

$$\frac{dE}{d(\rho_F x)} = \frac{dE}{d(\rho_H x)} \frac{\rho_H}{\rho_F} + \frac{dE}{d(\rho_C x)} \frac{\rho_C}{\rho_F} + \frac{dE}{d(\rho_O x)} \frac{\rho_O}{\rho_F} \quad (2)$$

F = formvar, H = hydrogen, C = carbon, O = oxygen.

The stopping powers for 5.48 MeV α 's were taken from (WBP 66). One obtains from Eq. (2):

$$\begin{aligned} \frac{dE}{d(\rho_F x)} &= [(21.82) \frac{16}{176} + 7.463 (\frac{96}{176}) + 6.892 (\frac{64}{176})] \times 10^2 \frac{\text{MeV cm}^2}{\text{g}} \\ &= 8.565 \times 10^2 \frac{\text{MeV cm}^2}{\text{g}} \end{aligned} \quad (3)$$

It was found that 5.48 MeV particles lost 0.089 ± 0.009 MeV in traversing 44 double layers of formvar.

$$\frac{dE}{d\rho_F x} = 8.565 \times 10^2 \text{ MeV cm}^2/\text{g}$$

$$dE = 0.089 \text{ MeV}$$

$$d(\text{Fx}) = \frac{0.089}{8.565 \times 10^2} \text{ g/cm}^2 = 1.04 \times 10^{-4} \text{ g/cm}^2 .$$

$$1 \text{ double layer} = 2.36 \text{ } \mu\text{g/cm}^2 \approx 2.4 \pm 0.2 \text{ } \mu\text{g/cm}^2 .$$

APPENDIX D

GAS HEATING MODEL

To estimate the instantaneous heating of the gas a calculation with the model given below is carried out.

When an object of cross-section A moves with uniform velocity v through a gas, it will displace a volume Avt in time t . The minimum velocity that must be imparted to the volume Avt is v . This way the gas in front of the object is transported just behind the object in time t . The work done in moving this amount of gas must be supplied by the object.

Suppose the proton beam traversing the gas heats a volume element of height h , width w and length ℓ to a temperature T_f . Due to buoyancy the volume element will rise, its terminal velocity should satisfy the equation

$$vt(\rho V - \rho \frac{VT_i}{T_f})g = \rho(vt\ell w)\frac{v^2}{2}.$$

V is the volume element = ℓhw ;

T_i is the temperature of the surrounding gas;

T_f is the temperature of the heated gas;

v is the terminal velocity;

ρ is the surrounding gas density;

g is the acceleration due to gravity.

The left side represents the change in potential energy when the heated volume rises the distance vt . The right side represents the energy needed to move the gas of volume $vt\ell w$ out of the way.

One obtains for the terminal velocity:

$$v = \left[\frac{2(T_f - T_i)}{T_f} hg \right]^{1/2}$$

Assume the total amount of energy E deposited in volume V is equal to the energy deposited in the gas during time $t = h/v$;

$$\text{so } E = t \rho S I$$

S is the stopping power of the gas for protons of the energy under consideration. I is the proton current.

The temperature rise of volume element V is then given by

$$E/(\rho V K) = T_f - T_i,$$

where K is the specific heat of the bombarded gas.

Substituting for E , V , and t one obtains:

$$\begin{aligned} T_f - T_i &= (h \rho S I) / (v \rho h w K) = S I / (v w K) \\ (T_f - T_i)^2 v^2 &= (T_f - T_i)^3 2 h g / T_f = S^2 I^2 / (K^2 w^2) \\ (T_f - T_i)^3 &= T_f S^2 I^2 / (2 h w^2 g K^2) \end{aligned}$$

This last equation can be easily solved by iteration.

Chosen units are:

$$S \text{ in } (\text{MeV cm}^2)/\text{g}$$

$$I \text{ in } \mu \text{ coulombs/sec}$$

$$K \text{ in cal/(g } ^\circ\text{C)}$$

$$\begin{aligned} \left(\frac{S I}{K} \right)^2 &= \left[\frac{\text{MeV cm}^2}{\text{g}} \frac{1.60 \times 10^{-6} \text{ erg}}{\text{MeV}} \frac{\text{cal}}{4.184 \times 10^7 \text{ erg}} \frac{10^{-6} \text{ coul/sec}}{1.60 \times 10^{-19} \text{ coul/proton}} \right. \\ &\quad \left. \times \frac{\text{g } ^\circ\text{C}}{\text{cal}} \right] \\ &= \left(\frac{1}{4.184} \right)^2 (^\circ\text{C})^2 \frac{\text{cm}^4}{\text{sec}^2} \end{aligned}$$

$$(T_f - T_i)^3 = \frac{T_f (C^\circ)^2 \text{cm}^4}{(4.184)^2 \text{sec}^2} \frac{S^2 I^2}{K^2} \frac{1}{2hw^2 g}$$

For the experiment on ^{20}Ne gas the values are $I = 0.5$ and 0.1 respectively.

$$w = 0.063 \text{ cm}, h = 0.114 \text{ cm}$$

$$S = 13.9$$

$$K = 0.246$$

For these values I find $T_f(I=0.5) = 321^\circ\text{K}$ and $T_f(I=0.1) = 304^\circ\text{K}$.

A 22 MeV proton loses .081 MeV in a 1 mil Kapton window.

The stopping power of 22 MeV protons in nitrogen is $20.88 \text{ MeV cm}^2/\text{g}$. When the gas pressure is 30 cm (oil) the energy deposited in the cell per proton is then:

$$\begin{aligned} \Delta E &= (4.75) (2.54 \text{ cm}) \frac{28 \text{ g}}{22.4 \times 10^3 \text{ cm}^3} \frac{30 \text{ cm}}{13.8 \times 76 \text{ cm}} \frac{20.88 \text{ cm}^2}{\text{g}} \text{ MeV} \\ &= 0.9 \times 10^{-2} \text{ MeV} \end{aligned}$$

So the total energy loss in gas and Kapton is 0.09 MeV per proton. The usual beam intensity was $0.5 \mu\text{amp}$.

$$\begin{aligned} \text{Power} &= (0.09 \text{ MeV}) (0.5 \times 10^{-6} \text{ coul/sec}) (1/1.6 \times 10^{-19} \text{ coul}) \\ &= 2.8 \times 10^{11} \text{ MeV/sec} \approx 0.01 \text{ calories/sec.} \end{aligned}$$

The gas cell body is made of brass and weighs 1450 g. Take the specific heat of brass at 0.09 cal/g , then the rate of temperature rise of the cell is

$$\frac{0.01}{(1450)(.09)} \frac{C^\circ}{\text{sec}} = 0.8 \times 10^{-4} \text{ C}^\circ/\text{sec}$$

Since the gas cell is in metal contact with the scattering chamber, no long term heating of the cell is expected to

result. The above assumes efficient cooling of the gas by the brass body of the cell.

APPENDIX E

CALCULATIONS FOR BEAM DEGRADER

Energy straggling for a beam of particles with nuclear charge z passing through a target of nuclear charge Z , atomic number A and density ρ is given by (EV 55):

$$\overline{(\Delta E)^2} = 4\pi z^2 e^4 (Z/A) (\rho X) N \quad (1)$$

where X is the distance of target traversed, N is Avagadro's number.

Suppose a proton beam with energy 21.65 MeV is to be degraded to 17 MeV. In (WBP 66) one finds the range of 21.65 MeV protons and 17 MeV protons in Al. The difference in range is the desired aluminum thickness; 0.2307 g/cm^2 . For lead one obtains 0.414 g/cm^2 .

To compare the energy spread from formula (1) above, consider

$$\frac{Z}{A} (\rho X) = (13/17) (0.2307 \frac{\text{g}}{\text{cm}^2}) = 0.111 \text{ g/cm}^2 \text{ for aluminum,}$$

$$\frac{Z}{A} (\rho X) = (82/207) (0.414 \frac{\text{g}}{\text{cm}^2}) = 0.164 \text{ g/cm}^2 \text{ for lead.}$$

Hence, aluminum is the better degrader. The actual energy spread for aluminum is:

$$\overline{\Delta E^2} = 1.565 \times 10^{-1} \frac{Z}{A} (\rho X) \text{ MeV}^2$$

$$\overline{\Delta E^2} = 0.132 \text{ MeV}^2 .$$

A 0.035" thick aluminum plate was used as degrader.

The 6061 aluminum alloy has the composition:

98.0 % Al

1.0 % Mg

0.6 % Si

0.20% Cr

0.25% Cu

0.05% impurities.

It is thus safe to use the ranges for protons in pure aluminum to calculate the expected energy loss using (WBP 66). 0.035" aluminum represents an areal density ρX :

$$\rho X = (2.7 \text{ g/cm}^3) (.035) (2.54) = 0.240 \text{ g/cm}^3.$$

From (WBP 66) a 21.65 MeV proton has a range 0.6610 g/cm^2 in aluminum. The range 0.421 g/cm^2 corresponds to a proton beam of 16.8 MeV.

The angular beam spread is given by

$$\theta = \frac{21(\text{MeV})}{2E(\text{MeV})} \sqrt{\frac{L}{L(\text{rad})}}$$

L = length in scatterer = 0.035"

E = proton energy

$L(\text{rad})$ = radiation length of aluminum = 8.9 cm

$$\therefore \theta = 3.3^\circ.$$

APPENDIX F

BAND RESOLUTION CALCULATIONS

TOOTSIE plots a number proportional to Et^2 against a number proportional to E where E is the energy of the particle and t is the flight time. One may rewrite:

$$Et^2 = \left(\frac{1}{2} mv^2 \right) (d/v)^2 = \frac{1}{2} md^2 \quad (1)$$

where d is the flight path. Hence the plot by TOOTSIE should be a set of straight bands, parallel to the x-axis, each band representing a mass. The width of the bands depends on energy resolution of the detector, time resolution of the beam pulse, flight path range, and time resolution of the electronics. The last can be ignored except for very low energy pulses, where it is extremely difficult to estimate.

$$\Delta Et^2 = \frac{\delta}{\delta E} (Et^2) \Delta E + \frac{\delta}{\delta t} (Et^2) \Delta t = t^2 \Delta E + 2Et \Delta t \quad (2)$$

$$\frac{\Delta Et^2}{Et^2} = \frac{\Delta E}{E} + 2 \frac{\Delta t}{t} \quad (3)$$

Δt has two contributing sources, δt the beam pulse width, and $\Delta d/v$ from the range of flight paths. Since $t = d/v$, Eq. (3) can be written

$$\frac{\Delta Et^2}{Et^2} = \frac{\Delta E}{E} + 2 \left(\frac{\delta t}{t} + \frac{\Delta d}{d} \right) \quad (4)$$

The three contributions limiting the mass resolution are independent of each other, so for a comparison with data the square root of the sum of their squares is appropriate.

ΔE was always 40 keV or better as measured from the FWHM of the 5.48 MeV alpha peak from an americium source. The percent error then varies inversely with E .

The average beam pulse width was 0.5 nsec. The percentage error varies inversely with flight time, hence with energy:

$$t = d/v = \frac{d}{c\sqrt{2}} \sqrt{\frac{mc^2}{E}}$$

maximum $E \sim 20$ MeV, minimum mc^2 of interest is 6×938 MeV;

$$d \sim 30 \text{ cm.}$$

$$\therefore t_{\min} \sim 12 \text{ nsec.}$$

$$t_{\max} = 12 \text{ nsec} + \text{RF} \sim 65 \text{ to } 84.$$

Hence the percent error contribution to $\frac{\Delta(Et^2)}{Et^2}$ varies from 8% to 1.2%.

The error due to path length variation is largest at small forward angles. The following calculation is for a 0.040" beam width (horizontal dimension) and a 0.040" wide front slit with the detector at 15° to the beam. The range of flight path distance is calculated for 90% of the particles reaching the detector.

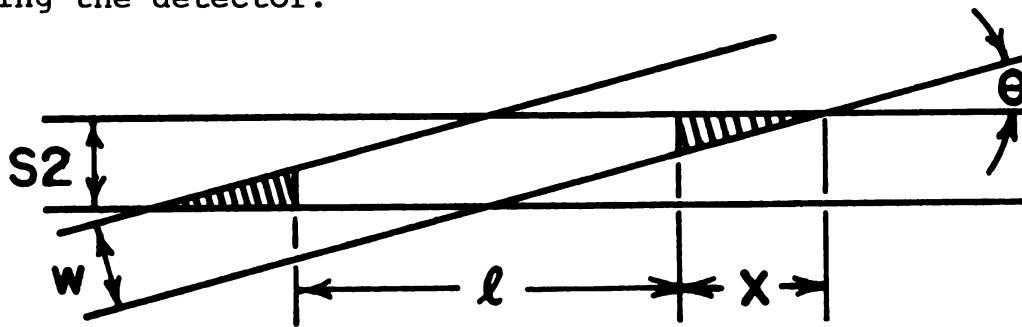


Figure 23. Range of Flight-Distance for 90% of Particles Reaching the Detector.

$$\text{Total area} = \frac{S^2 w}{\sin \theta}$$

$$\text{Shaded area} = x^2 \tan \theta$$

For shaded area to be 10% of total area requires:

$$\frac{S^2 w}{\sin \theta} \frac{1}{10} = x^2 \tan \theta$$

$$x = \frac{S^2 w \cos \theta}{10 \sin^2 \theta}$$

$$l = \frac{w}{\sin \theta} + \frac{S^2}{\tan \theta} - 2x$$

where l is the range of path lengths desired. For $\theta = 15^\circ$,

$S = 0.040''$, $w = 0.040''$, I find $l = 0.0256'' = .65\text{cm}$.

For a flight distance of 26 cm, the percent contribution to $\frac{\Delta E t^2}{E t^2}$ is then $2(0.65/26.0)100\% = 5\%$.

APPENDIX G

TIME-OF-FLIGHT CROSS-SECTION INTEGRATION RELATED FORMULAS

Some details for calculating cross-sections from angular distributions.

Below are tabulated a few fortran statements representing equations used in the cross-section calculations.

The equation to calculate the number of channels corresponding to energy loss in gas and window:

$$\text{ECHC} = ((\text{RA}(\text{L}) - \text{H}) * \text{P} * 2. / 7.6 / .2241 + 2.0) * 2.335 / 10. ** 2 * \text{Z1}(\text{M3}) ** 1.207 * \text{Z2} / (\text{Z1}(\text{M3}) **.6667 + \text{Z2} **.6667) ** 1.5 * \text{ECAL}$$

(RA(L)-H) is the average distance the reaction product travels in the gas; this varies with angle.

P is the gas pressure in cm Hg.

Z1(M3) is the charge of the reaction product, the average for the expected products for a particular mass band is used.

Z2 is the charge of the target gas.

ECAL is the number of channels per MeV of particle energy from the energy calibration curve.

An integration factor :

$$\text{F}(\text{L}) = (\text{COSD}((\text{A}(\text{L}-1) + \text{A}(\text{L})) / 2.) - \text{COSD}((\text{A}(\text{L}) + \text{A}(\text{L}+1)) / 2.)) / \text{NM}(\text{L})$$

A(I) are angles at which data was taken.

NM(L) is the number of monitor counts for data taken at angle A(L).

The factor combining most constants and geometric variables:

$$G(L) = (CNM/Q) * (H/Bl) * ((R/P) * (SIND(BA)/Z) * (.2241/.17854) * (.76/.6452) * (.1602/.15625) * (.6283/.6025) * ((T+273.1)/273.1))$$

- CNM is the number of monitor counts for the calibration run.
- Q is the total collected charge for the calibration run in 10^{-8} coulombs.
- P is the pressure in inches Hg for the calibration run.
- T is the gas temperature in °C assumed to be equal to room temperature.
- H is the distance from S_1 to S_2 (see Figure 70) in inches.
- R is the mean flight path length to S_1 in inches.
- Bl is the width of S_2 in inches.
- BA is the angle at which data is taken, hence this is $A(L)$.
- Z is the number of atoms per target molecule.

The number $(.15625)(.17854)(6.452)$ represents the area of S_1 in cm^2 .

The quantity $F(L)*G(L)*NSY$ is then the contribution to the total cross-section for data taken at angle $A(L)$. NSY is the number of counts in a specific energy spectrum corrected for the low energy cutoff.

APPENDIX H

SETUP PROCEDURE

To set up the electronics systems a pulser is used to simulate detector pulses at the preamplifier input. First the time-pickoff control logic pulse output is monitored with a cathode ray oscilloscope; and its sensitivity is set so that it just does not free run and triggers only occasionally on random noise. After this adjustment the pulser is turned on and the fast timing logic is checked out. The fast discriminators are checked for multiple triggering. The delays for the RF stop pulse and the start pulse to the TAC are adjusted so that pulses which arrive simultaneously at the fast anticoincidence circuit also would arrive simultaneously at the TAC (if the 25 nsec anticoincidence requirement would not be in effect). The TAC pulses generated by the pulser are monitored with a ND 160 multichannel analyzer. A flat, continuous random time spectrum should be observed. The single channel analyzer pulses to the slow coincidence module have to arrive at the same time. This is done by turning the delay knob on a SCA module while monitoring with the scope. The veto pulse is similarly adjusted, choosing pulse length and delay on the gate and delay generator module. The output of the Universal Coincidence is checked next. It should give logic pulses if the veto is disabled, and should have

no output if the pulser is also connected to the veto preamplifier. The logic pulse from the slow coincidence gates the energy and TAC pulses. The linear signals have to have the correct delay to be passed by the linear gate and stretchers. The amplifier provides a properly delayed unipolar linear signal. The TAC pulse is delayed with a 427A delay amplifier (not shown in the electronics diagram). The linear gate and stretcher controls are adjusted so linear signals are 3 μ sec long and arrive at the same time at the ADC's.

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