

FRAGMENT ENERGY CORRELATIONS IN THE
FISSION OF ^{231}Pa BY 11.5-MeV PROTONS

BY

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INTRODUCTION

Shortly after the discovery of fission, Bohr and Wheeler¹ had great success in understanding fission cross sections as a function of excitation energy by considering the nucleus as a charged liquid drop. It soon became apparent that this model was inadequate in that it predicts approximately equal size fragments, or what is known as symmetric fission. In reality the spontaneous and thermal neutron induced fission of nuclei in the actinide region of the periodic table yield fragment masses characteristic of asymmetric fission.² This can be understood by adding fragment shell structure to the liquid drop model.³ Particularly important is the closure of an energy shell at 82 neutrons and another at 50 protons. This doubly magic condition for ^{132}Sn makes a fragment of mass near 132 amu energetically favorable.

In 1958 Jensen and Fairhall⁴ did a radiochemical analysis of the fragments from ^{226}Ra bombarded by 11-MeV protons. They observed a triply peaked mass yield distribution. This was the first indication that, for a particular nuclidic species, competition could exist between the symmetric fission mode resulting from liquid drop effects and the asymmetric fission mode resulting from shell effects.

Further work by Britt, Wegner, and Gursky⁵ in 1963 showed that the modes could be differentiated, even when the yield of one of the modes was small. The differentiation came from analysis of the fragment energetics which included a calculation of \bar{D} , the distance at which the total kinetic of the two fragments would be equal to the electrostatic

repulsion energy of two point charges with charge to mass ratio equal to that of the fissioning nucleus, and included analysis of the increase in variance of the kinetic energy distribution.

More recently, in 1969, Schmitt, Plasil, and Ferguson⁶ observed fragment energy correlations in the fission ^{232}Th by protons with energies between 8 and 13 MeV. In their case, as in the work to be presented here, the symmetric mode is barely visible in the total mass yield, but is quite visible on a three-dimensional representation of yield as a function of both the mass of the fragments and the total kinetic energy of the two fragments. Although not discussed by Schmitt et. al.⁶ the lower kinetic energy for symmetric fission is presumably due to the fact that the symmetric fission fragments require greater deformation energy and provide less kinetic energy than the asymmetric fission fragments. Consequently, as a function of both mass and total kinetic energy on a three-dimensional plot, the symmetric fission events appear as a hill in the valley between the two asymmetric peaks, but for lower kinetic energies (see, for example, PLATE II or reference 6). This, however, is not the case for ^{235}U thermal-neutron induced fission studied by Schmitt, Neiler, and Walter⁷ and ^{233}U neutron induced fission studied by Pleasonton⁸, where none of the symmetric fission mode appears.

These results of Schmitt et. al.⁶ on the proton-induced fission of ^{232}Th indicate that it would be interesting to observe proton-induced fissions for other nuclei in the region of the periodic table between ^{233}U , which shows no symmetric component, and ^{226}Ra which has a triply

peaked yield. The nuclide ^{231}Pa is a particularly interesting case intermediate between ^{226}Ra and ^{233}U since the mass number is below ^{232}Th and the Z^2/A value, or fissibility parameter, is above that of ^{232}Th .

THE EXPERIMENT

The present measurements consisted of bombarding targets of ^{231}Pa with 11.5-MeV protons from the Tandem Van de Graaff Accelerator of the Nuclear Science Laboratory at Kansas State University. Coincident measurements of the kinetic energies of the fragment pairs were made with surface barrier detectors. The excitation energy is great enough that both first chance and second chance (after emission of one neutron) fission result. From the approximate conservation of momenta and of nucleon number applying to fission, close approximation to the masses of fragments can be determined for each fission event.

The hemispherical chamber⁹ designed by Mr. Erich Feldl and located on the L-3 beam line was used to allow interchangeable targets and measurements in vacuum. This chamber has facilities for mounting detectors from 2 in. to 4 in. from the target at 30° intervals. The frame on which the detectors are mounted can be rotated while the chamber is evacuated, in a 360° arc with respect to the beam. The targets are mounted on a ladder which holds up to 5 targets, any one of which may be placed in the beam at any time and can also be rotated 360° about the beam.

In practice the detectors were placed at 180° to each other and 90° to the beam to minimize scattered beam on the two detectors. The B-detector was $2\frac{3}{4}$ in. from the target while the A-detector was mounted $2\frac{1}{4}$ in. from the target. This assures that all fission fragments recorded in B have their complementary fragments recorded in A.

Collimators of 1/16 in. aluminum with 3/8 in. holes were placed approximately 1/4 in. and 3/4 in. from the deflector faces. The targets were rotated so that the normal to the surface was 45° from the beam in order to minimize scattering of fission fragments and energetic protons from the target frames. During preliminary runs, data were taken with first one detector and then the other detector viewing the fragments through the backing foil to allow determinations of fragment energy losses in the carbon backing of the targets.

The detectors used were Ortec model F-040-100-60 silicon surface barrier detectors. Each has an active area of 100mm^2 , a depletion depth of 60 microns at 90 V and a resistivity of 145 ohm-cm. This depletion depth stops fission fragments and alpha particles emitted by the target, but not scattered protons. The low resistivity results in a low charge collection time.

Two types of targets were required to provide both measurement and calibration. The calibration targets were a deposit of ^{232}Th of 100 g/cm^2 on a 40 g/cm^2 carbon backing. These targets were made in the radioactive materials evaporator at KSU. The targets for measurement were 79 g/cm^2 deposits of ^{231}Pa on 40 g/cm^2 carbon backing. These targets were made at Oak Ridge National Laboratory. One further foil of ^{252}Cf , from which spontaneous fissions are observed was used to set up and initially, to calibrate. This foil has a cover foil to prevent contamination of the chamber.

The equipment used for the measurements included (refer to PLATE I) two Ortec model 260 time pick-off (TPO) units and their associated Ortec

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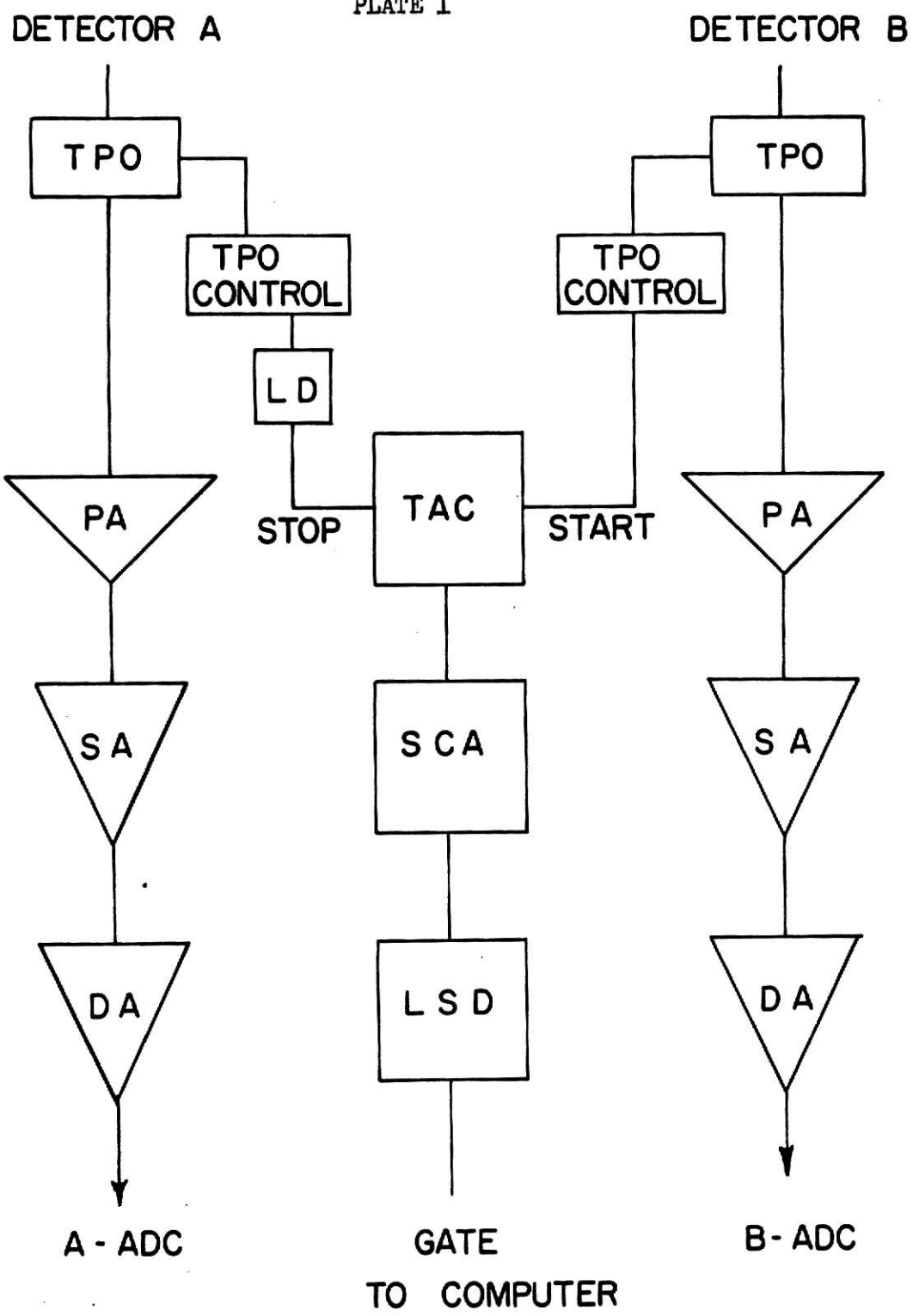
PLATE I

Block diagram of the electronics used.

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PLATE 1



model 403A TPO control units, two Ortec model 451 spectroscopic amplifiers (SA), two Ortec model 109A charge sensitive preamplifiers (PA), two Ortec model 427A delay amplifiers (DA), a Nanosecond Systems model 260 linear delay (LD), an Ortec model 437A time-to-amplitude converter (TAC), an Ortec model 406A single channel analyzer (SCA), and an Ortec model 416A logic shaper and delay (LSD) unit. All the units are NIM modules except the TPO's and the preamplifiers, which were powered by the TPO control units, and a preamplifier power supply respectively. Also used was the PDP-15 model 30 computer with two Nuclear Geoscience model 6040 analog-to-digital converters (ADC). The setting-up procedure included the use of the Technical Measurements Corporation (TMC) 4096-channel multichannel pulse height analyzer.

In practice the ^{252}Cf source was loaded with the ^{232}Th and ^{231}Pa targets, and the chamber was evacuated. The fission-fragment and alpha-particle pulse heights from ^{252}Cf were then observed on an oscilloscope at the preamplifiers to make certain the detectors and preamplifiers were working properly. The thresholds of the TPO control units were set so that they responded to fission fragment (much larger amplitude) pulses but not to the alpha-particle pulses. The pulses from the TPO control output for the A-side were then delayed by 32 nsec, and this pulse fed to the stop side of the TAC. The TPO control output for the B-side was connected to the start side of the TAC and the TAC scale set for 100 nsec/8v. The time spectrum from the TAC was recorded in the TMC multichannel analyzer, and the limits of the single channel analyzer were set to respond only when the time signal fit into the character-

istically doubly-peaked time spectra obtained from the variable velocities of the fragments. This assures no pulse heights will be recorded unless both pulses of a pair come from a single fission event and no alpha-particle or scattered proton pulse heights are recorded.

The pulse out of the SCA was connected to the LSD. The LSD takes the short duration output pulse of the SCA and lengthens the pulse to a preset duration and height for use as a gating signal. It also incorporates a variable delay, which was set at a minimum for this experiment. A pulse of 8-V amplitude and 5- sec duration was found to be adequate to gate the ADC's at the computer interface.

The preamplifiers were then connected to the SA's and the SA's to the DA's. At this point a pulser was used to set the delay on the DA's so that the detector pulses and the gating pulse were coincident in time.

The pulse heights were recorded by the PDP-15 model 30 computer of the Nuclear Science Laboratory with a modified version of the dual parameter pulse height analysis program supplied by Digital Equipment Corporation.

This program is named Pulse Height Analysis for Two-Dimensional Event Recording (PHA2EV). It allows writing of events on magnetic tape using the full accuracy of the ADC's. The original program from DEC provides for only a 64 X 64 data array stored in the memory core of the computer, while PHA2EV allows a 4096 X 4096 array. This extra resolution was desirable to avoid problems of finite grid size when converting from pulse-height vs pulse-height array to total kinetic

energy vs mass array. The computer has inadequate memory for a 4096 X 4096 array, so the individual events (a pair of pulse heights) are recorded on magnetic tape for retrieval at a later time.

The original modifications were accomplished in collaboration with Dr. G. Seaman of the Physics Department at KSU. In this form the program added a 1024 word buffer which it filled with events in a linear fashion while also recording the same data in a 64 X 64 array in core. When the buffer was filled, processing is interrupted and the events are transferred to tape. The buffer was then filled again, etc. An individual DECTAPE (a small roll of magnetic tape used with the PDP-15) holds 100 such transfers. Another group working at the accelerator, Mr. J. Gray and Dr. J. Legg, noted that this computer program did not function properly with high counting rates (over about 10 events per sec.), but instead omitted counts. Where the list should have been ABAB..., in places the list was instead ABBAB... or ABAABAB.... If this happens when observing fission fragment pulse heights it would appear as accidental coincidences between a pulse height from one fission event and pulse height from another fission event. Initially no problem was encountered, but one run at high counting rate showed obvious signs of dropped counts. These included many more counts in the symmetric fission region, due to coincidence between two low energy fragments from two different fissions, and a spurious group corresponding to pairs of high energy fragments from two fission events.

To circumvent this difficulty a modified version of PHA2EV was

used. This version tagged the A-ADC words by turning on bit zero, the bit that is used in one's compliment arithmetic to indicate a negative number. FORTRAN uses two's compliment arithmetic. Its use necessitated the use of TESTEV, a MACRO subroutine written by Mr. J. Gray and Dr. G. Seaman, which searched for dropped counts in the data list and modified the list accordingly. In the case of an AA record it removed the first A and in a BB record it removed the last B. It then packed the list with zeros at the end and turned off bit zero of the A-ADC words so they would be properly recognized by a FORTRAN routine.

CALIBRATION AND DATA ANALYSIS

The mass-dependent energy formula of Schmitt, Kiker, and Williams¹⁰ was used to obtain a kinetic energy and a mass for each fragment. ²³²Th bombarded by 11.5-MeV protons was used instead of ²⁵²Cf spontaneous fission as the standard of energy. From this information an array of yield as a function of total kinetic energy of the two fragments and mass of each fragment was calculated. Also calculated were the mean total kinetic energies, variance in total energy, and yield for all kinetic energies as a function of mass of each fragment.

The general scheme for calibration is as follows:

- 1) Obtain a ²⁵²Cf pulse height spectra making sure the detectors are operating in the saturation region.
- 2) Locate the midpoints between the three-quarter amplitude points of the two peaks, and call the greater pulse height P_1 and the lesser P_h .
- 3) The calibration is then given by

$$E = (a + a' * M) * X + b + b' * M,$$

where X is the pulse height, E is the energy of the fragment in MeV and

$$a = 24.0203 / (P_1 - P_h),$$

$$a' = 0.03574 / (P_1 - P_h),$$

$$b = 89.6083 - a * P_1,$$

$$b' = 0.1370 - a' * P_1.$$

One parameter, M , is missing. If the mass is known then the

energy can be computed. A practical solution, used by Bishop¹¹, consists of using a linear energy calibration and conservation of both momentum and mass to obtain a provisional mass and then using this mass to get a corrected energy through the mass dependent formula,

The linear energy calibration consists of combining the measured values of P_l and P_h in

$$E = S*X + B,$$

where

$$S = 24.40/(P_l - P_h),$$

$$B = 79.40 - P_h*S$$

Since the fission fragments are non-relativistic in the energy range studied, conservation of linear momentum can be written as

$$M_1*V_1 = M_2*V_2,$$

where V is the velocity of the fragment, M is the mass of the fragment, and 1 and 2 refer to the two fragments of a pair.

This implies that

$$M_1*E_1 = M_2*E_2, \quad (1)$$

where E is the kinetic energy of the fragment.

By neglecting neutron emission, which is typically less than 2%, conservation of mass can be written as

$$M_1 + M_2 = A, \quad (2)$$

where A is the mass of the compound nucleus (232 amu for $^{231}\text{Pa} = p$).

By adding M_1*E_2 to both sides of eq. (1) and using eq. (2)

$$M_1 = E_2*A/E_t \quad \text{and} \quad M_2 = A - M_1,$$

where

$$E_t = E_1 + E_2.$$

This procedure yields a provisional energy, which gives a provisional mass. Together these provide an energy and a mass for both fragments of a pair through the mass dependent formula. The process could be iterated again by calculating a corrected mass with the corrected energy, but is terminated here because the results change by only about 1/2% upon further iteration.¹¹

Originally this procedure was followed exactly, but it led to two severe problems. First the variances in the kinetic energy distribution as a function of mass changed systematically depending on which detector viewed the fragments through the backing foil. This was due either to failure to account for finite thickness of the backing foil or differences in thickness in the backing and cover foils on the ^{252}Cf calibration source. Secondly, the PDP-15 was in the installation phase, and it was not uncommon for the computer to cease to function at two hour intervals. Since the ^{252}Cf source was not very active, about 4 hours were required to obtain sufficient events to calibrate properly. This led to many frustrating data losses.

Both of these problems were eliminated by using the ^{232}Th target bombarded with 11.5-MeV protons. The ^{252}Cf three-quarter points were then extrapolated from the ^{232}Th three-quarter points in a linear fashion by relying on previous runs of ^{232}Th bombarded with 11.5-MeV protons preceded by a ^{252}Cf calibration. This made a calibration possible in 15 minutes and, to first order, made a correction for the energy lost in the backing foil.

In order to make the calibration and convert the raw data, two programs for the PDP-15 were written in FORTRAN IV. FORTRAN source decks as well as flow charts of these programs can be found in the appendix.

The first, called EVDAT, reads the data from tape and then creates two 256-channel singles spectra, one for each ADC. This is used to find the three-quarter points and parameters for a linear energy fit if the spectra is the spontaneous fission of ^{252}Cf . It was used in the ^{232}Th calibration to obtain the three-quarter points. The calibration spectra were smooth enough that the three-quarter points were easy to pick out visually. Smoothing the data over five points was done in order to facilitate computer searching of these three-quarter points. Such smoothing should not change the midpoint between the three-quarter points but allows the computer to readily find the three-quarter points. This program also plots the counts vs channel for both the raw and averaged data.

The second program, called CON, reads the data from tape and then calculates the total energy vs mass array. It must be given the ^{252}Cf parameters P_l and P_h along with the parameters for a linear energy fit for each detector. It prints the calculated array and then plots an average of the events vs mass spectra at a total energy from 120 to 215 MeV in 5-MeV steps. It also plots the total mass distribution and events vs total energy for masses 53 to 173 amu in 4-amu steps. At the same time it plots the events vs total energy, it also calculates and prints the mean total energy and variance about that mean.

RESULTS

The results appear as a three-dimensional plot of events vs the mass of the fragments for various values of the total kinetic energy of the fragment pairs (PLATE II). Also included are plots (PLATE III) of the mean total energy as a function of mass and the variance about that mean as a function of mass and a plot (PLATE IV) of the yield for all total kinetic energies as a function of mass. The data were averaged over 5 amu to smooth the plots. For the last three plots only data for mass greater than 116 amu (half the mass of the compound nucleus) is presented because the calculations have symmetry built into them.

The data taken with ^{232}Th at 11.5-MeV bombarding energy were also analyzed to compare with Schmitt et. al.⁶ The average total energy vs mass agrees within about 1% while the variance in the present data is 10% to 15% lower in the region between 116 amu and 130 amu. A difference of this amount can be expected from different corrections for finite backing thickness in the calibrations and from different cut-off points in the distributions used.

It should be noted that the three-dimensional plot shows no symmetric peak in yield above 170-MeV total energy. At these higher kinetic energies, only asymmetric fission results.

The increase in variance at symmetry should also be noted. No such increase is seen in the data taken with ^{232}Th . Since there are about 800 events/amu in this area, the variance should have no more than a

PLATE II

Three-dimensional plot of events vs the mass of the fragments for various values of the total kinetic energy for the 11.5-MeV proton-induced fission of ^{231}Pa .

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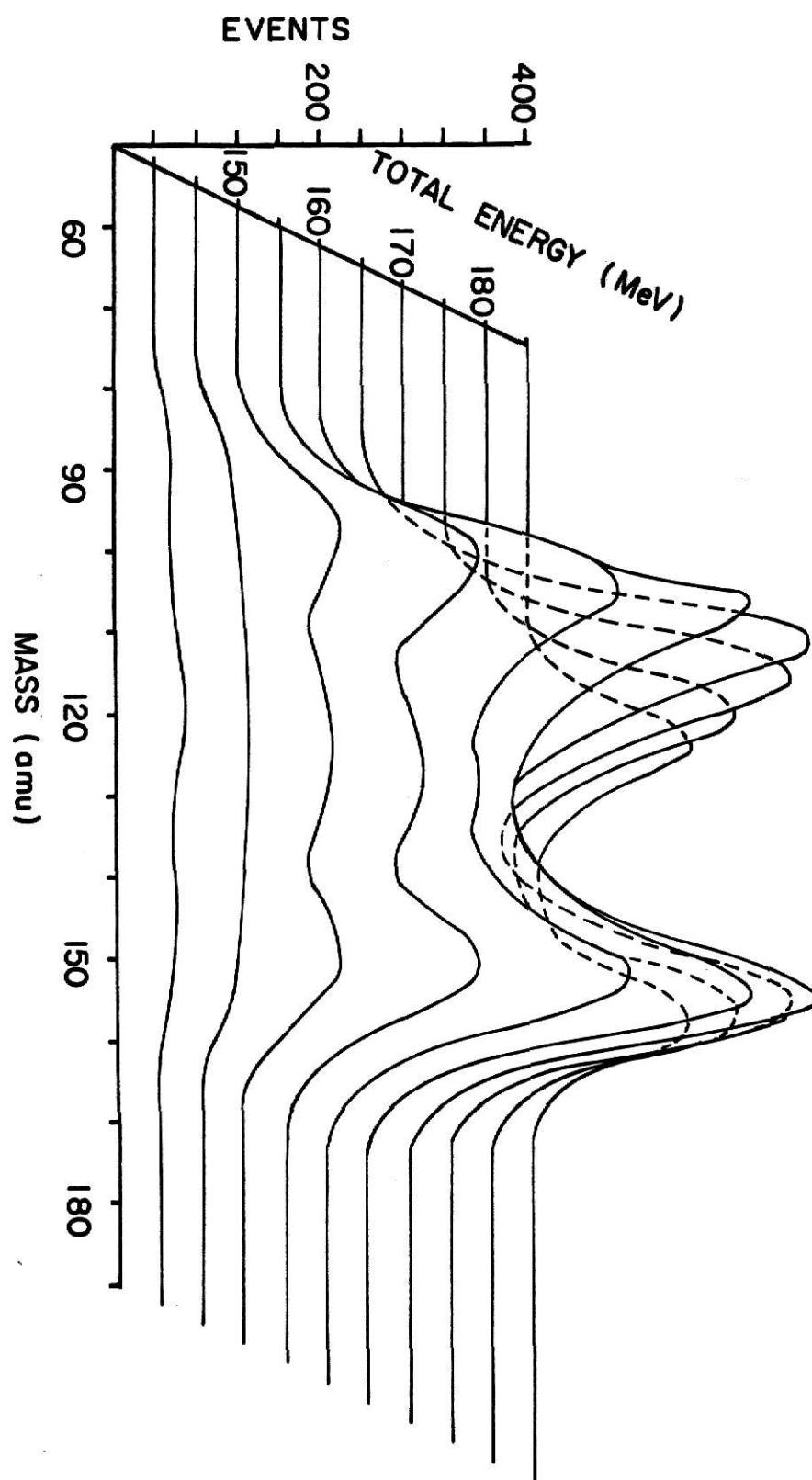


PLATE III

Plots of the mean total kinetic energy of the two fragments and variance about that mean as functions of the mass of the heavy fragment from the 11.5-MeV proton-induced fission of ^{231}Pa .

PLATE III

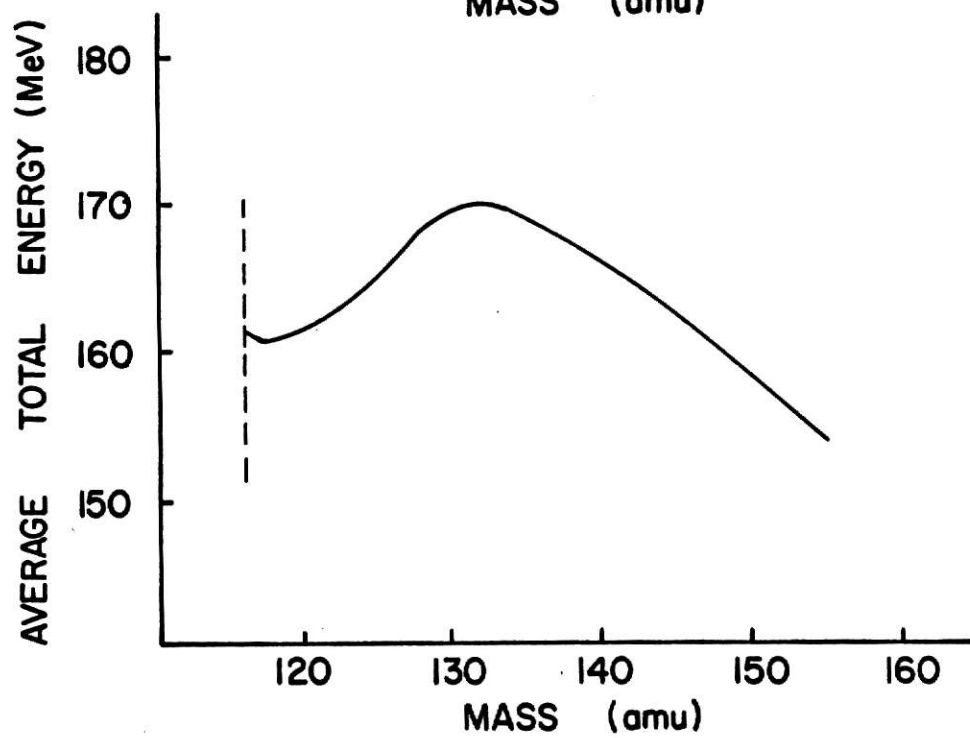
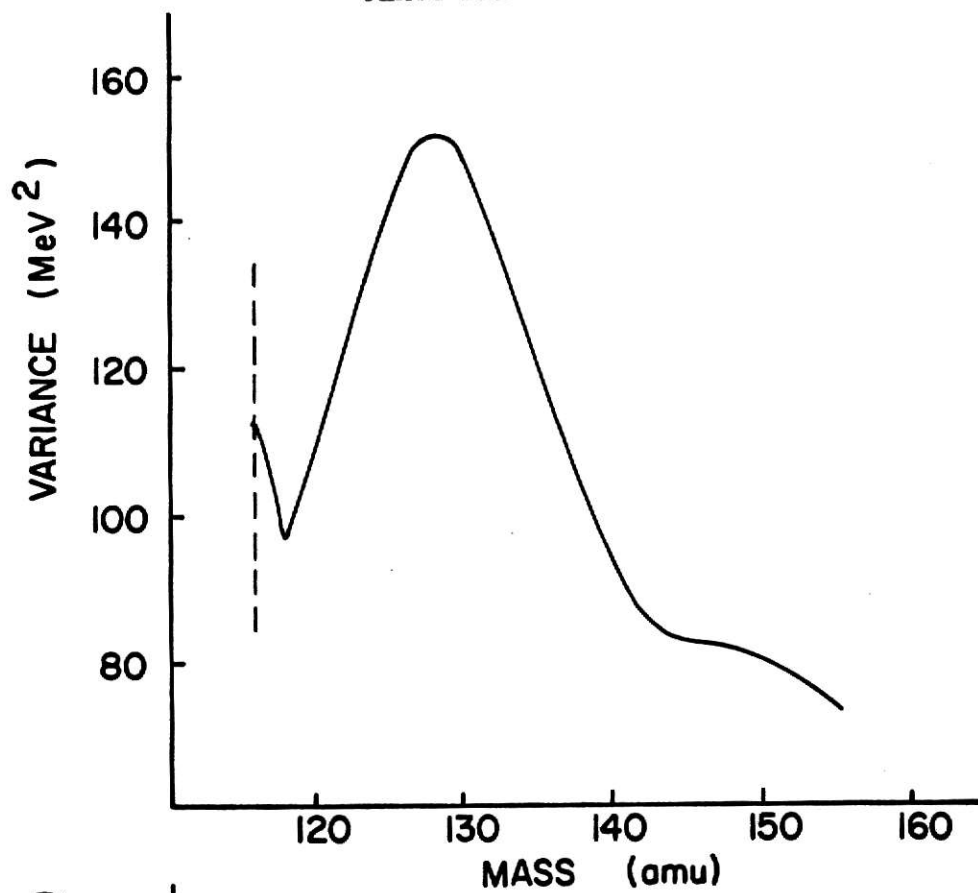
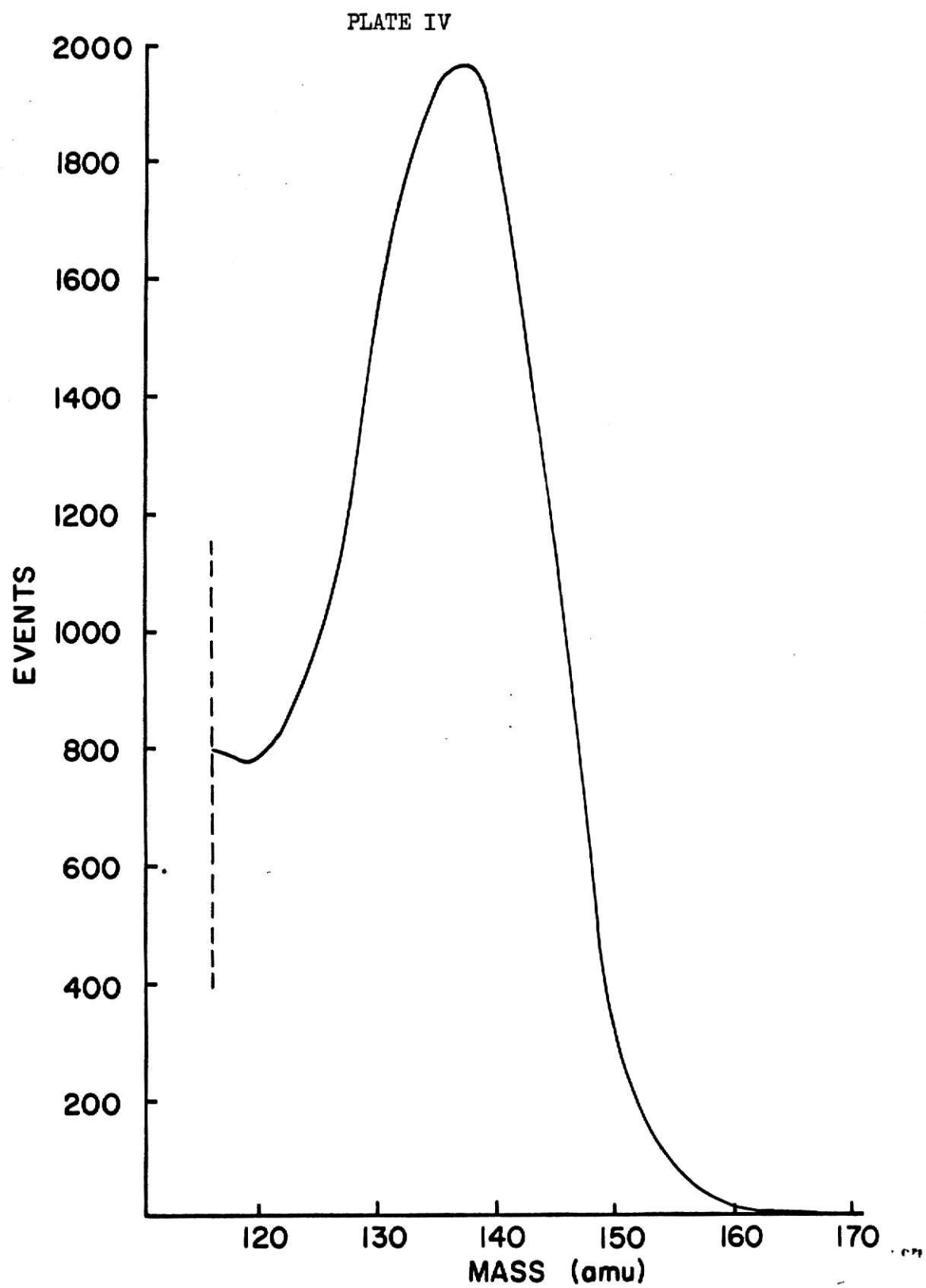


PLATE IV

Plot of the total events observed as a function of the mass of the heavy fragment for the 11.5-MeV proton-induced fission of ^{231}Pa .



3% error, but the peak corresponds to about 10%. The computer code provided only two points in this mass region, and so instead a point for each mass was calculated by hand. A smooth curve fits each of the resulting points. This can partially be attributed to accidental coincidences which are more likely to appear at symmetry, but, since no such peak was seen in the ^{232}Th data, it is more likely due to an intrinsic fission property of the excited ^{232}U . This detail warrants further study.

Recently C. F. Tsang and J. B. Wilhelmy³ have given theoretical insights into the mechanism for production of both symmetric and asymmetric fission from the same nuclide (^{222}Ra) based on detailed calculations by Moller and Nilsson¹², Pauli and Ledergerber¹³, and Nix.¹⁴ As yet no detailed calculations have been published for fission of ^{232}U (^{231}Pa plus a proton).

Since the excitation energy of the compound nucleus created by capture of 11.5-MeV protons by ^{231}Pa is approximately the same as that of capture of 13.0-MeV protons by ^{232}Th and the binding energies of a neutron in the ^{232}U and ^{233}Pa compound nuclei are similar, the energy available for first and second chance fission for the two cases are the same within about 10%. In both cases, the excitation of the ^{233}Pa compound nucleus is greater, but only by approximately 1 MeV. Thus we may compare, at least in a qualitative manner, the present data of 11.5-MeV proton induced fission of ^{231}Pa with the 13-MeV proton induced fission of ^{232}Th of reference 4. The three-dimensional plot appears to contain more symmetric fission for the ^{232}Th case. This

indicates the symmetric yield increases with increasing mass number rather than increasing fissibility parameter Z^2/A . However, this result might partly result from the higher excitation energy in the ^{232}Th case. The curves for average total energy and variance are similar within statistics, except for the rise in variance and a higher average total kinetic energy (about 4 MeV) for the ^{231}Pa data near symmetry.

CONCLUSION

Data obtained in this experiment with ^{232}Pa fission indicate a general trend for nuclei near mass 232 amu to exhibit a symmetric peak in yield at lower total kinetic energy than the total kinetic energy of the asymmetric peaks.

As the experiment stands there are at least four questions left unanswered:

- 1) Have all possibilities been eliminated for the increase in variance at symmetry for the ^{231}Pa data being instrumental?
- 2) Does this increase in variance for symmetry remain at different excitation energies?
- 3) Does the proton induced fission of ^{231}Pa exhibit the same increase in symmetric yield as the compound nucleus excitation energy is increased as is seen by Schmitt et. al.⁶ for the proton induced fission of ^{232}Th ?
- 4) What other nuclei exhibit both a symmetric and asymmetric fission yield.

It is hoped that further experiments with varying proton bombarding energy and other nuclides will answer these questions.

APPENDIX

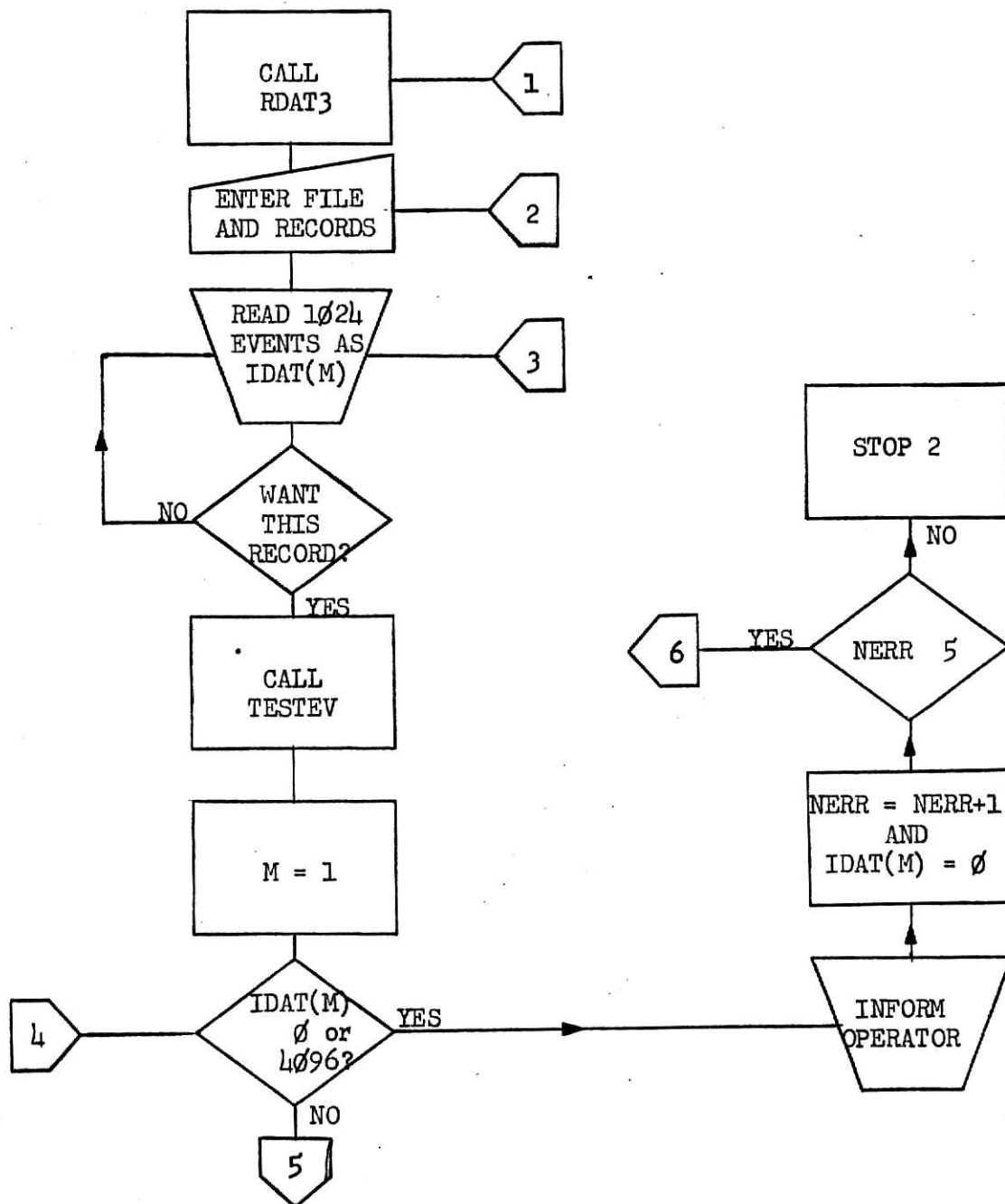
Included in the appendix are flow charts and FORTRAN source listings of the two computer programs used in the calibration and data analysis.

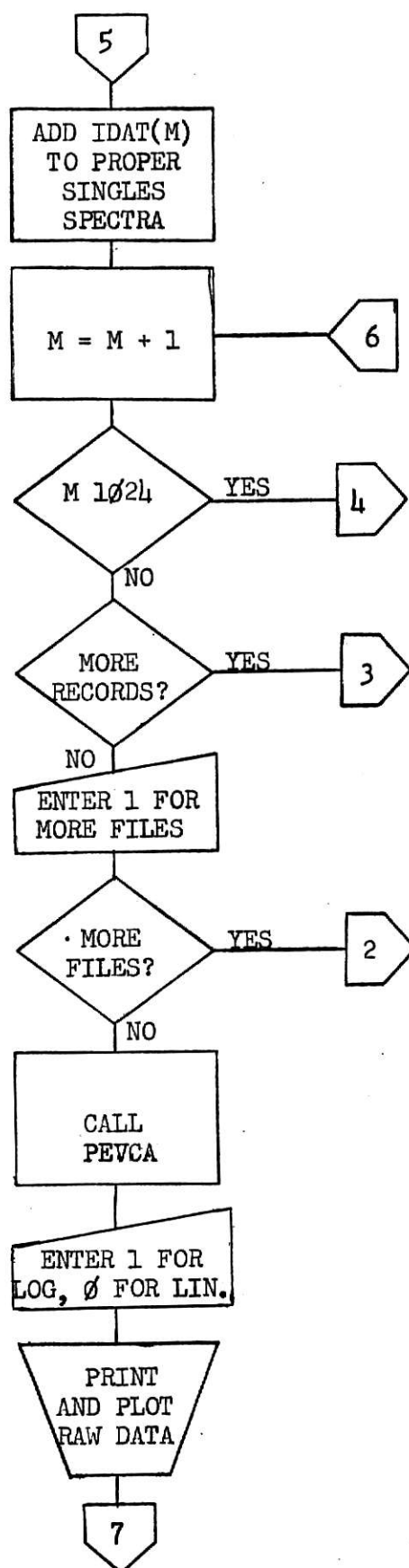
Due to the limited core available to the background user on a PDP-15 the routines are broken into subroutines. The main programs, EVDAT and CON, act as drivers, deciding which of the subroutines are resident in core while the other subroutines are ready to be read in from tape. The system routines CHAIN and EXECUTE were used to facilitate this process.

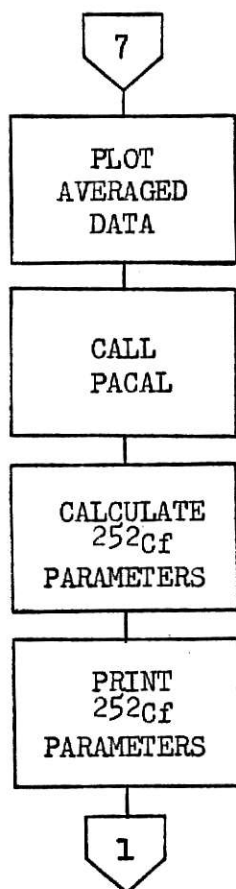
The subroutine R20128 is included and is a general subroutine used to read files on DECTAPE created by CON.

The flow charts are designed for someone familiar with FORTRAN and are correct in logic but not detailed. The flow is from top to bottom unless noted. Subroutine TESTEV is explained in the text.

FLOW CHART FOR PROGRAM EVDAT







C
C
C
C
C

FILE EVDAT
 COMPACTING A 4096 X 4096 EVENT RECORDING DATA ARRAY
 INTO TWO 256 LINES AND PRINTING AND PLOTTING THE RESULTS

COMMON /ALPHA/ IDAT(1024),IA(256),IB(256),FN(2)

COMMON /BETA/ P(120)

COMMON /GAMMA/ IAV(256),IBA(256)

COMMON /RHO/ SL,B,BP

DATA BLNK/LH /

ZERO = 0

DO 100 I=1,120

P(I)=BLNK

100
1

CONTINUE

CALL RDATA

CALL PEVCA

CALL PACAL

GO TO 1

STOP

END

```

C      FILE RDAT3
C      SUBROUTINE RDAT3 FOR EVDAT
C
      SUBROUTINE RDAT3
      COMMON /ALPHA/ IDAT(1024),IA(256),IB(256),FN(2)
      IERR = 0
1      WRITE (1,101)
101     FORMAT (11H FILE? (A9) )
      READ (1,102) FN
102     FORMAT (A5,A4)
      CALL FSTAT (3,FN,N)
      IF (N.EQ.-1) GO TO 2
      WRITE (1,103)
103     FORMAT (25H FILE NOT FOUND ON .DAT3 )
      GO TO 1
2      CALL SEEK (3,FN)
      WRITE (1,301)
301     FORMAT (11H ZERO? 1=NO )
      READ (1,105) M
      IF (M.EQ.1) GO TO 30
      DO 1000 M=1,256
      IA(M)=0
      IB(M) = 0
1000    CONTINUE
30      WRITE (1,104)
104     FORMAT (10H RECORDS? /5H FROM)
      READ (1,105) I
105     FORMAT (I4)
      WRITE (1,106)
106     FORMAT(3H TO)
      READ (1,105) J
      IF (J.LT.I) GO TO 1001
      WRITE (2,110) I,J
      WRITE (2,111) FN(1),FN(2)
111     FORMAT (10H0FROM FILE ,A5,A4)
110     FORMAT (31H1RECORDS ARE TO BE ENTERED FROM ,I4,2HTO, I4)
      N=0
7      N=N+1
      KB=0
      DO 4 K=1,16
      KA=KB+1
      KB=KB+64
      READ (3) (IDAT(M),M=KA,KB)
4      CONTINUE
      IF (N.LT.I) GO TO 7
      CALL TESTEV (IDAT,1024)
      DO 2000 M=1,1024
      IF(IDAT(M).GT.4096) GO TO 51
      IF(IDAT(M).LT.0) GO TO 52

```

```

20000 CONTINUE
      DO 5 M=1,1023,2
      ACHAN=FLOAT(IDAT(M))/16. + 0.5
      NC=ACHAN
      IF (NC.EQ.0) NC=1
      IA(NC) = IA(NC) + 1
5     CONTINUE
      DO 6 M=2,1024,2
      ACHAN=FLOAT(IDAT(M))/16. + 0.5
      NC=ACHAN
      IF (NC.EQ.0) NC = 1
      IB(NC) = IB(NC) + 1
6     CONTINUE
      IF (N.LT.J) GO TO 7
      WRITE (1,302)
302   FORMAT (19H OTHER FILES? 1=YES )
      READ (1,105) M
      IF (M.EQ.1) GO TO 1
      RETURN
1001  WRITE (1,150)
150   FORMAT (15H THAT'S A NO-NO )
      GO TO 2
51    WRITE (1,151) M,N
151   FORMAT (23H POSSIBLE ERROR IN NO. ,I4,15H OF RECORD NO. ,I3)
      IERR = IERR + 1
      IF (IERR.GT.5) GO TO 500
      IDAT(M) = 0
      IF (2*(M/2)-M) 200,201,202
52    WRITE (1,152) M,N
152   FORMAT (18H NEG VALUE IN NO. ,I4,15H OF RECORD NO. ,I3)
      IERR = IERR + 1
      IF (IERR.GT.5) GO TO 500
      IDAT(M) = 0
      IF (2*(M/2)-M) 200,201,202
500   WRITE (1,153)
153   FORMAT (16H TOO MANY ERRORS )
      STOP 2
202   WRITE (1,205)
205   FORMAT (3H **)
      STOP 3
200   KIM=M+1
      IDAT(KIM) = 0
      GO TO 20000
201   KIM = M-1
      IDAT(KIM) = 0
      GO TO 20000
      STOP
      END

```

```

C      FILE PEVCA
C
C      SUBROUTINE PEVCA FOR EVDAT
C
      SUBROUTINE PEVCA
      COMMON /ALPHA/ IDAT(1024),IA(256),IB(256),FN(2)
      COMMON /BETA/ P(120)
      COMMON /GAMMA/ IAV(256),IBA(256)
      MAM = 0
      MBM = 0
      DO 10 M=1,254
      E = FLOAT(IA(M-2) + IA(M-1) + IA(M) + IA(M+1) + IA(M+2))/5.
      IAV(M) = E + 0.499
      E = FLOAT(IB(M-2) + IB(M-1) + IB(M) + IB(M+1) + IB(M+2))/5.
      IBA(M) = E + 0.499
10     CONTINUE
      IAV(1) = 0
      IAV(2) = IA(2)
      IAV(3) = IA(3)
      IAV(255) = IA(255)
      IAV(256) = IA(256)
      IBA(1) = 0
      IBA(2) = IB(2)
      IBA(3) = IB(3)
      IBA(255) = IB(255)
      IBA(256) = IB(256)
      DO 8 M=2,256
      MAM=MAX0(IA(M),MAM)
      MBM=MAX0(IB(M),MBM)
8     CONTINUE
      CA = FLOAT(MAM)/120.
      CB = FLOAT(MBM)/120
40     WRITE (1,107)
107    FORMAT (21H 0=NORMAL 1=LOG PLOT)
      READ (1,105) IND
      ITOTA = 0
      ITOTB = 0
      IF (IND.EQ.1) GO TO 51
61     IF (IND.EQ.1) GO TO 52
62     WRITE (2,108) MAM
      DO 70 K=1,256
      ITOTA = ITOTA + IA(K)
      ITOTB = ITOTB + IB(K)
70     CONTINUE
108    FORMAT(6H1IAM = ,I10 )
105    FORMAT (13)
      WRITE (2,121) ITOTA
121    FORMAT (22H0TOTAL COUNTS IN A ADC ,3X,I8)
      WRITE (2,109) (IA(M),M=1,256)
109    FORMAT (1H012I10)

```

```

WRITE (2,108) MAM
WRITE (2,121) ITOTA
IF (IND.EQ.0) WRITE (2,122)
IF (IND.EQ.1) WRITE (2,123)
DO 30 M=1,256
CALL PLT (CA,IA(M),IND)
30 CONTINUE
IF(IND.EQ.0) WRITE (2,122)
IF(IND.EQ.1) WRITE (2,123)
DO 35 M=1,256
CALL PLT (CA,IAV(M),IND)
35 CONTINUE
WRITE (2,110) MBM
110 FORMAT (6H1BM = ,I10 )
WRITE (2,124) ITOTB
124 FORMAT (26H0THE TOTAL COUNTS IN ADC B ,3X,I8)
WRITE (2,109) (IB(M),M=1,256)
WRITE (2,110) MBM
WRITE (2,124) ITOTB
IF (IND.EQ.0) WRITE (2,122)
IF (IND.EQ.1) WRITE (2,123)
122 FORMAT (30H1WHAT FOLLOWS IS A LINEAR PLOT)
123 FORMAT (35H1WHAT FOLLOWS IS A LOGARITHMIC PLOT)
DO 31 M=1,256
CALL PLT (CB,IB(M),IND)
31 CONTINUE
IF (IND.EQ.0) WRITE (2,122)
IF (IND.EQ.1) WRITE (2,123)
DO 41 M=1,256
CALL PLT(CB,IBA(M),IND)
41 CONTINUE
WRITE (1,120)
120 FORMAT (7H MORE=1)
READ (1,105) M
IF (M.EQ.1) GO TO 40
RETURN
51 QA = ALOG(CA*120.)/120.
CA = QA
GO TO 61
52 QA = ALOG(CB*120.)/120.
CB = QA
GO TO 62
STOP
END

```



```

C      FILE PLT
C      SUBROUTINE FOR EVDAT
C      ALSO USED IN CON
C
      SUBROUTINE PLT (C,J,I)
      COMMON /BETA/ P(120)
      DATA AST,BLNK/1H*,1H /
      IF (J.EQ.0) GO TO 4
      IF (I.EQ.0) GO TO 10
      PLOT = ALOG(FLOAT(J))/C + 0.5
1      M=PLOT
      IF(M.GT.120) M=120
      P(M)=AST
4      WRITE (2,101) J,(P(K),K=1,120)
101     FORMAT (1H I6,1H*120A1)
      IF (J.NE.0) P(M) = BLNK
      RETURN
10     IF(C.LT.1.) C = 1.
      PLOT = FLOAT(J)/C + 0.5
      GO TO 1
      STOP
      END

```

```

C      FILE PACAL
C      SUBROUTINE FOR EVDAT
C
      SUBROUTINE PACAL
      COMMON /GAMMA/ IAV(256), IBA(256)
      COMMON /RHO/ SL,B,BP
      N = 0
1      N = N + 1
      IM = 0
      DO 400 M=1,256
      IF (IAV(M).LT.30) GO TO 400
      IF (IAV(M).GT.IM) IM = IAV(M)
      E = 3.*FLOAT(IM)/4.
      EP = FLOAT(IAV(M))
      IF (EP.LE.E) GO TO 401
400      CONTINUE
401      IF (IM.EQ.0) WRITE (1,105)
105      FORMAT (8H ERROR 5)
      MU = M
      DO 402 M=1,256
      EP = FLOAT(IAV(M))
      IF (EP.GE.E) GO TO 403
402      CONTINUE
403      ML = M
      MX = 0
      504      Y1 = IAV(ML-1)
      Y2 = IAV(ML)
      X1 = ML-1
      D = Y1 - Y2
      IF (D.EQ.0.) GO TO 404
      SL = 1./D
      XL = X1 + (E-Y1)*SL
      GO TO 405
404      XL = FLOAT(ML) - 0.5
      505      Y1 = IAV(MU-1)
      Y2 = IAV(MU)
      X1 = MU - 1
      D = Y1 - Y2
      IF (D.EQ.0.) GO TO 406
      SL = 1./D
      XU = X1 + (E-Y1)*SL
      GO TO 407
406      XU = FLOAT(MU) - 0.5
407      IF (MX.EQ.1) GO TO 505
      XH = (XU + XL)/2.
      IN = IM
      DO 500 M=MU,256
      IF (IAV(M).GT.IM) IM = IAV(M)
      IF (IM.EQ.IN) GO TO 500

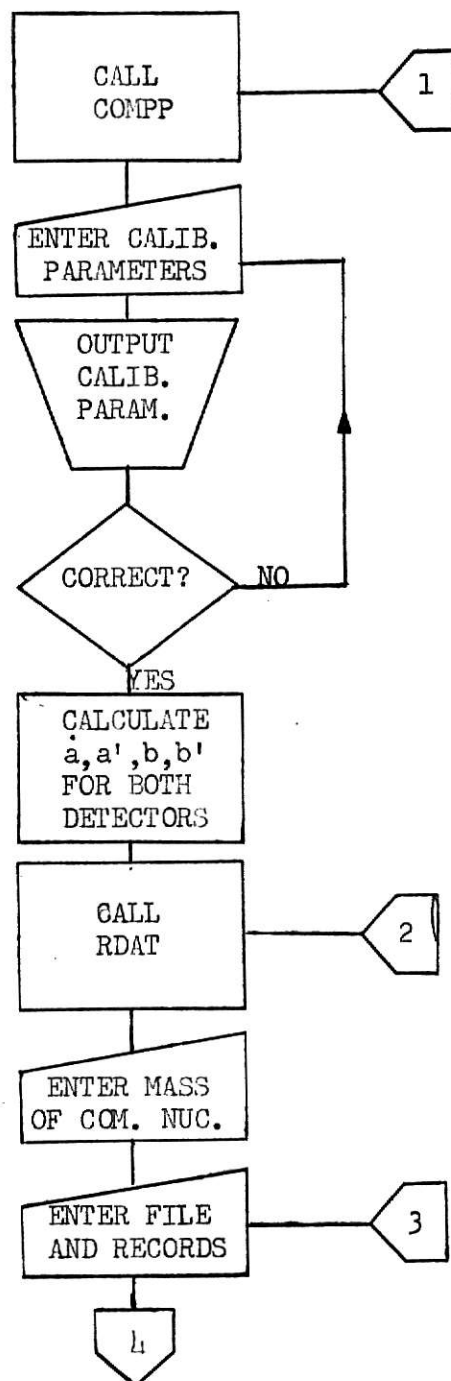
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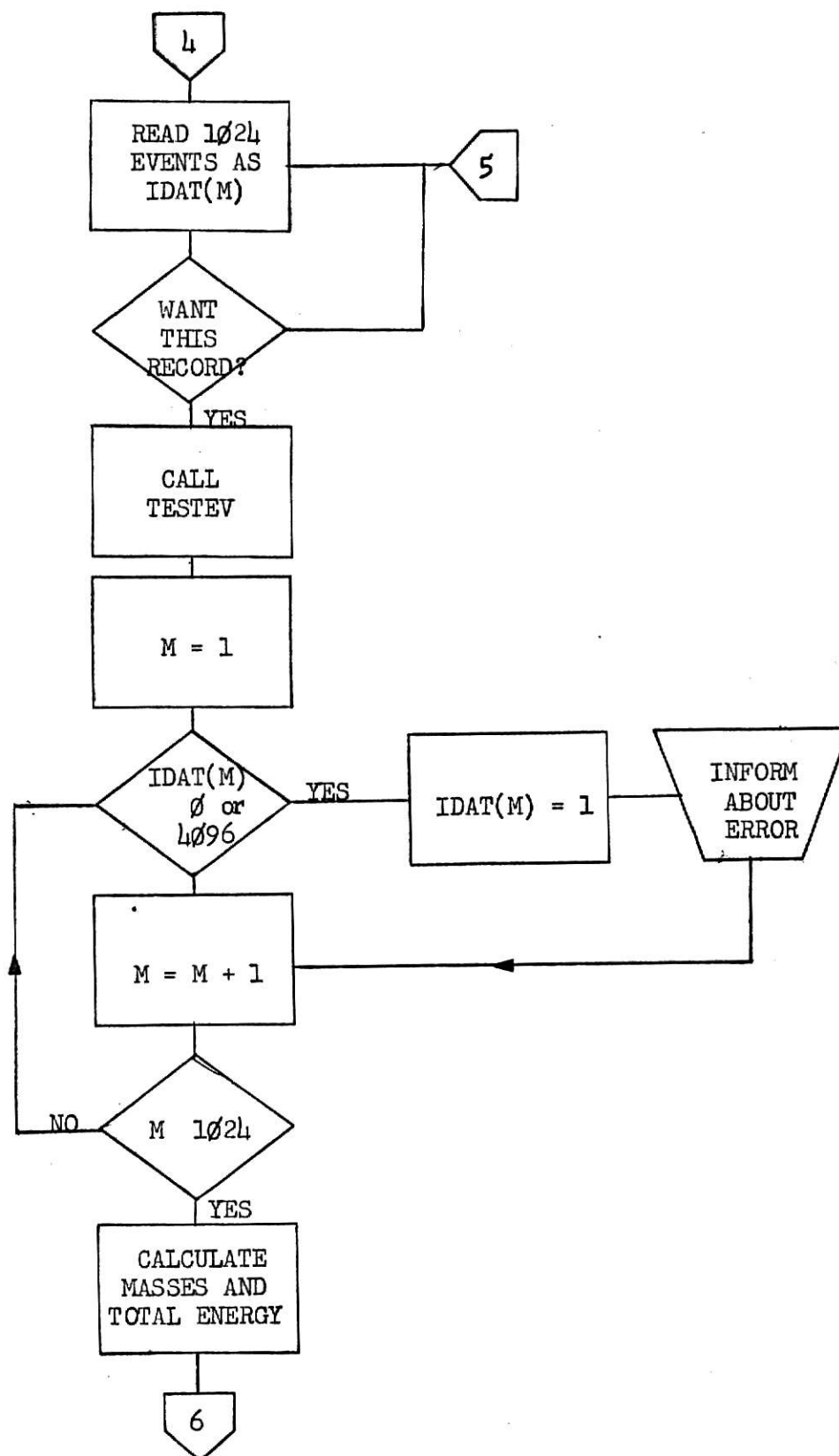
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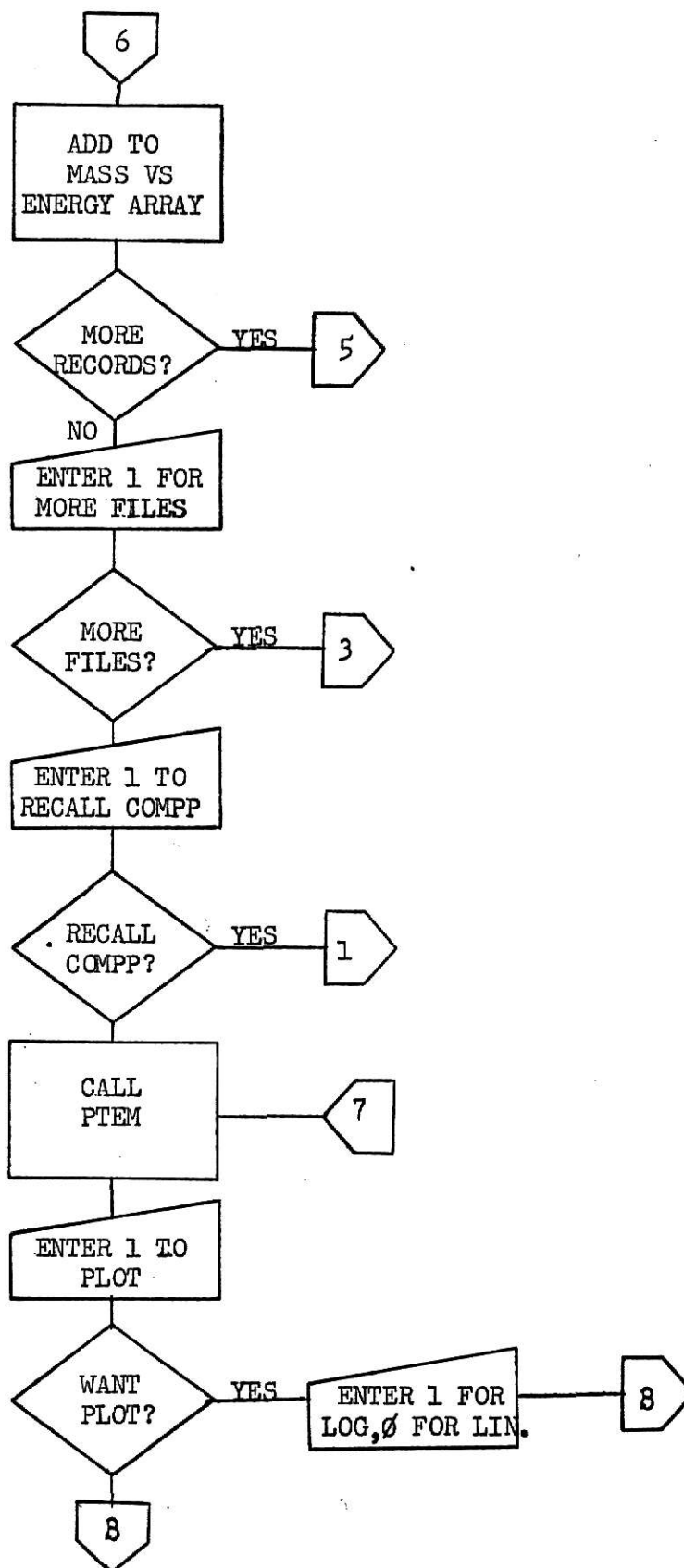
      E = 3.*FLOAT(IM)/4.
      EP = FLOAT (IAV(M))
      IF (EP.LT.E) GO TO 501
500  CONTINUE
501  MP = M
      DO 502 M=MU,256
      EP = FLOAT(IAV(M))
      IF (EP.GE.E) GO TO 503
502  CONTINUE
503  ML = M
      MU = MP
      MX = 1
      GO TO 504
505  XL = (XU + XL)/2.
      SL = 21.4/(XL-XH)
      EH = 79.4
      EL = 103.8
      B = EL - SL*XL
      BP = EH - SL*XH
      WRITE (2,101) EH,XH,SL,BP
101  FORMAT (6H1EH = F6.2,5X,5HXH = F6.2,5X,4HE = E10.4,
112H *CHANNEL + F8.2)
      WRITE (2,102) EL,XL,B
102  FORMAT (6H0EL = F6.2,5X,5HXL = F6.2,5X,4HB = F8.2)
      DO 700 M=1,256
      IAV(M) = IBA(M)
700  CONTINUE
      IF (N.EQ.1) GO TO 1
      RETURN
      END

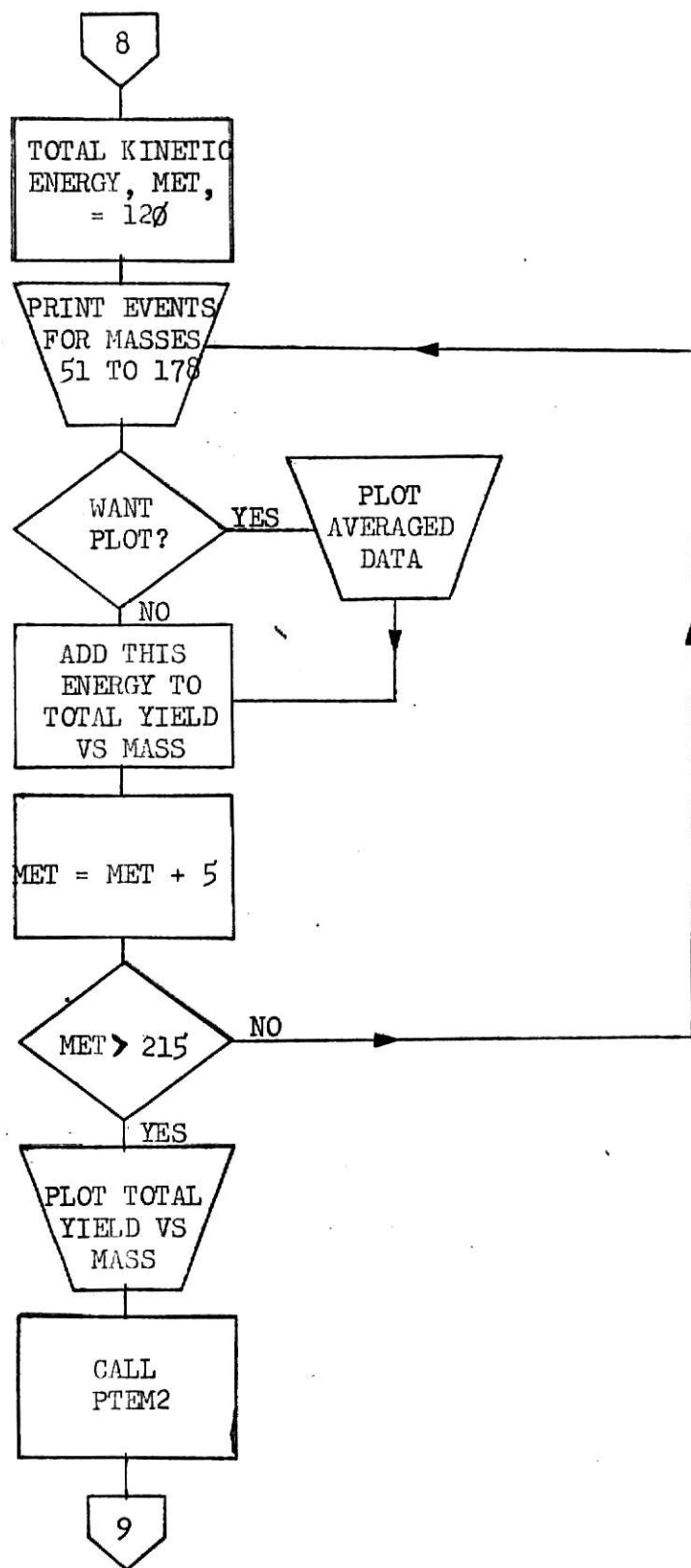
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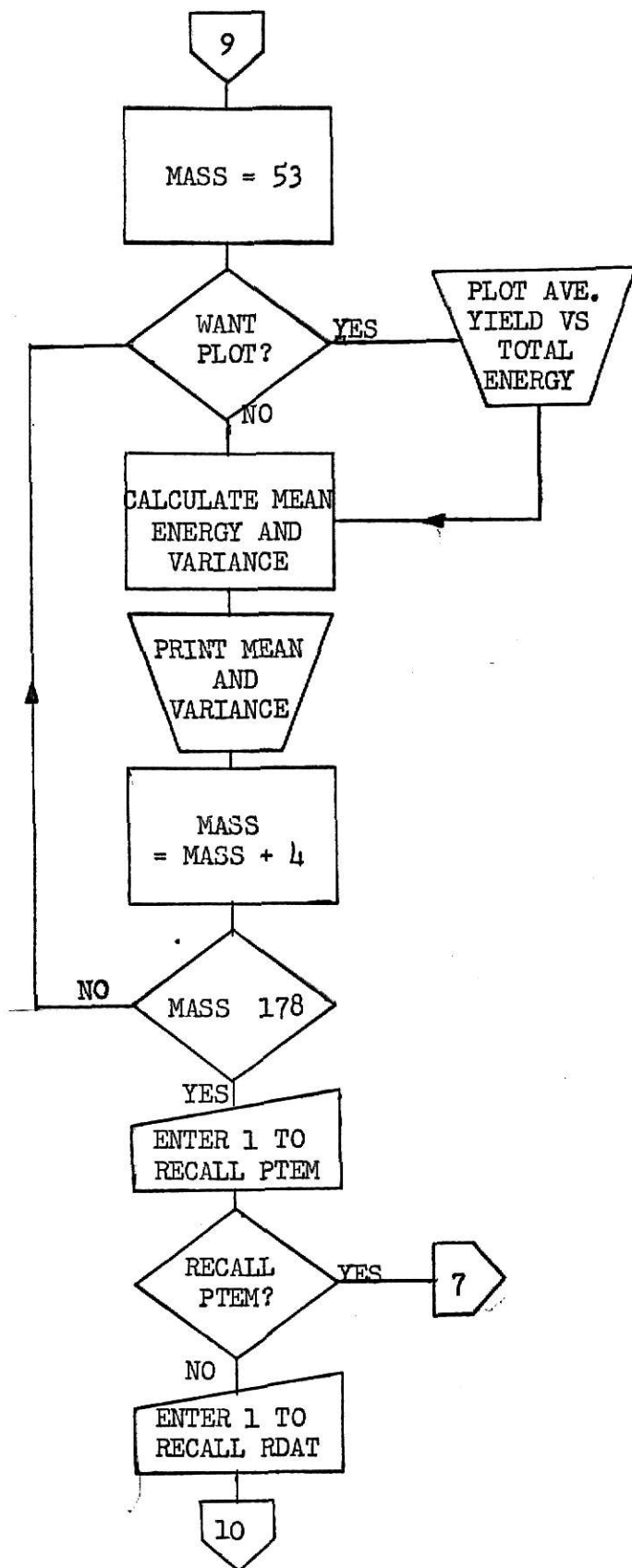
FLOW CHART FOR PROGRAM CON

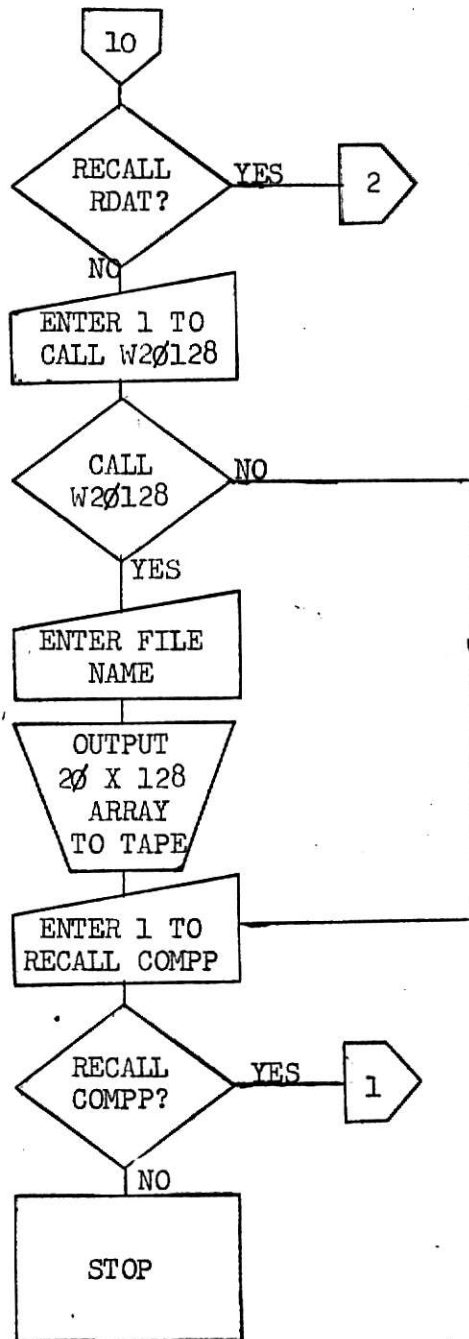












```

C      FILE CON
C
C      MAIN PROGRAM FOR CONVERSION OF E-E TO TE-M
C
COMMON /ALPHA/ IDAT(1024),ICON(20,128),FN(2)
COMMON /GAMMA/ A1,A2,AP1,AP2,B1,B2,BP1,BP2,SL1,SL2,BE1,BE2
COMMON /BETA/ P(120)
COMMON /ZETA/ IAV(129),IND,NDC

C
1      CALL COMPP
2      CALL RDAT
WRITE(1,104)
104    FORMAT(8H COMPP=1 )
READ (1,102) N
IF(N.EQ.1) GO TO 1
3      CALL PTEM
CALL PTEM2
READ (1,102) IND
IF(IND.EQ.1) GO TO 3
WRITE (1,105)
105    FORMAT(14H 1=RDAT AGAIN )
READ (1,102) N
IF(N.EQ.1) GO TO 2
WRITE (1,103)
103    FORMAT (10H W20128=1 )
READ (1,102) N
IF (N.EQ.1) CALL W20128
WRITE (1,101)
101    FORMAT(8H 1=AGAIN )
READ (1,102) N
102    FORMAT(14)
IF (N.EQ.1) GO TO 1
STOP
END

```

```

C      FILE COMPP
C      SUBROUTINE COMPP FOR CON
      SUBROUTINE COMPP
      COMMON /GAMMA/ A1,A2,SP1,AP2,B1,B2,BP1,BP2,SL1,SL2,BE1,BE2
      C = 24.0203
      D = 0.03574
      E = 89.6083
      F = 0.1370
      G = 16.
1      WRITE (1,101)
101     FORMAT(31H THE FOLLOWING IS FOR THE A ADC)
      WRITE (1,102)
102     FORMAT(32H ENTER PARAMETERS IN THIS ORDER; ,/6H SLOPE,
1/9H CONSTANT, /7H H-PEAK,/7H L-PEAK )
      READ (1,103) SL1
103     FORMAT(F10.0)
      READ (1,103) BE1
      READ (1,103) PH1
      READ (1,103) PL1
      WRITE (1,104)
104     FORMAT (14H NOW FOR B ADC )
      READ (1,103) SL2
      READ (1,103) BE2
      READ (1,103) PH2
      READ (1,103) PL2
      WRITE (1,105) SL1,BE1,PH1,PL1,SL2,BE2,PH2,PL2
105     FORMAT (4F15.5)
      WRITE (1,106)
106     FORMAT (14H0RIGHT? (1=NO) )
      READ (1,107) N
107     FORMAT (I4)
      IF (N.EQ.1) GO TO 1
      WRITE (1,108)
108     FORMAT(9H RIGHT ON)
      C1 = (PL1-PH1)*G
      C2 = (PL2-PH2)*G
      SL1 = SL1/G
      SL2 = SL2/G
      A1 = C/C1
      A2 = C/C2
      AP1 = D/C1
      AP2 = D/C2
      B1 = E-A1*PL1*G
      B2 = E-A2*PL2*G
      BP1 = F-AP1*PL1*G
      BP2 = F-AP2*PL2*G
      RETURN
      END

```

```

C      FILE RDAT FOR MAIN FOR CONVERSION OF E-E TO TE-M
C
      SUBROUTINE RDAT
      COMMON /ALPHA/ IDAT(1024),ICON(20,128),FN(2)
      COMMON /GAMMA/ A1,A2,AP1,AP2,B1,B2,BP1,BP2,SL1,SL2,BE1,BE2
      WRITE(1,250)
250    FORMAT(4H A= )
      READ(1,251) a
251    FORMAT(F4.1)
      WRITE (1,252) A
252    FORMAT (1H F6.1)
1      WRITE (1,101)
101    FORMAT(11H FILE (A9) )
      READ (1,102) FN(1),FN(2)
102    FORMAT(A5,A4)
      CALL FSTAT(3,FN,N)
      IF (N.EQ.-1) GO TO 2
      WRITE (1,103)
103    FORMAT (25H FILE NOT FOUND ON .DAT3 )
      GO TO 1
2      CALL SEEK (3,FN)
      WRITE (1,201)
201    FORMAT (7H ZERO=1 )
      READ (1,105) KLM
      IF (KLM.NE.1) GO TO 203
      DO 202 I=1,20
      DO 204 J=1,128
204    ICON(I,J) = 0
202    CONTINUE
203    WRITE (1,104)
104    FORMAT (9H RECORDS?, /5H FROM )
      READ (1,105) K
105    FORMAT (I4)
      WRITE (1,106)
106    FORMAT (3H TO)
      READ (1,105) L
      IF (L.LT.K) GO TO 1000
      WRITE (1,107) FN(1),FN(2),K,L
      WRITE (2,107) FN(1),FN(2),K,L
107    FORMAT(11H0FROM FILE ,A5,A4,14H RECORDS FROM ,I4,2X,3HTO ,I4//)
      NERR = 0
      N = 0
3      N = N + 1
      KB = 0
      DO 4 M=1,16
      KA = KB + 1
      KB = KB + 64
      READ (3) (IDAT(KI),KI=KA,KB)
4      CONTINUE

```

```

IF (N.LT.K) GO TO 3
CALL TESTEV (IDAT,1024)
DO 2000 M=1,1024
IF(IDAT(M).GT.4096) GO TO 51
IF(IDAT(M).LT.0) GO TO 51
2000 CONTINUE
DO 5 KI = 1,1023,2
X1 = FLOAT(IDAT(KI))
X2 = FLOAT(IDAT(KI+1))
E1 = X1*SL1 + BE1
E2 = X2*SL2 + BE2
ET = E1 + E2
AM1 = E2*A/ET
AM2 = A - AM1
E1 = (A1 + AP1*AM1)*X1 + B1 + BP1*AM1
E2 = (A2 + AP2*AM2)*X2 + B2 + BP2*AM2
ET = E1 + E2
AM1 = E2*A/ET
AM2 = A - AM1
ET = (ET-115.)/5.
ET = ET + 0.5
IF (ET.LT.1.0) GO TO 6
IF(ET.GE.21.) GO TO 6
M1 = AM1 + 0.5 - 50.
M2 = AM2 + 0.5 - 50.
IF (M1.LE.0) GO TO 6
IF (M2.LE.0) GO TO 6
IF (M1.GT.128) GO TO 6
IF (M2.GT.128) GO TO 6
I = ET
ICON(I,M1) = ICON(I,M1) + 1
ICON(I,M2) = ICON(I,M2) + 1
5 CONTINUE
GO TO 12
6 NERR = NERR + 1
GO TO 5
12 IF (N.LT.L) GO TO 3
WRITE (1,1050) NERR
1050 FORMAT(1H I6)
WRITE (1,108)
108 FORMAT(20H MORE FILES? (1=YES) )
READ (1,105) N
IF (N.EQ.1) GO TO 1
RETURN
51 WRITE (1,109)
109 FORMAT(24H DELETING POSSIBLE ERROR )
IDAT(KI) = 1
GO TO 2000
1000 WRITE (1,110)
110 FORMAT (10H TRY AGAIN )
GO TO 2
STOP
END

```

```

C      FILE PTEM
C      SUBROUTINE PTEM FOR CON
C      FILE PTEM2 IS A CONTINUATION OF PTEM
C      THE PROGRAM WAS DIVIDED TO USE LESS CORE
C
      SUBROUTINE PTEM
      DIMENSION MT(129)
      COMMON /ALPHA/ IDAT(1024),ICON(20,128),FN(2)
      COMMON /BETA/ P(120)
      COMMON /ZETA/ IAV(129),IND,NDC
      DATA BLNK/1H /
      DO 100 I=1,120
100    P(I) = BLNK
      WRITE (1,101)
101    FORMAT(12H WANT PLOT=1 )
      READ (1,102) IND
      IF (IND.NE.1) GO TO 37
      WRITE (1,105)
105    FORMAT(13H 1 = LOG PLOT,5X,10H0 = LINEAR )
      READ (1,102) NDC
102    FORMAT(14)
      DO 10 J=1,128
37     MT(J) = 0
      DO 1 I=1,20
      MET = 120 + (I-1)*5
      WRITE (2,103) MET
103    FORMAT (16H1TOTAL ENERGY = 13,13H (+OR-2.5)MEV////)
      WRITE(2,104) (ICON(I,M),M=1,128)
104    FORMAT(1H0,5X,110,7(5X,110))
      ITOT = 0
      IMAX = 0
      DO 2 J=3,126
      FAV = FLOAT(ICON(I,J-2) + ICON(I,J-1)*2 + ICON(I,J)*3
1+ICON(I,J+1)*2 + ICON(I,J+2))/9.
      IAV(J) = FAV + 0.5
      ITOT = ITOT + IAV(J)
      IMAX = MAX0(IMAX,IAV(J))
2     CONTINUE
      IAV(1) = ICON(I,1)
      IAV(2) = ICON(I,2)
      IAV(127) = ICON(I,127)
      IAV(128) = ICON(I,128)
      IF(IND.NE.1) GO TO 20
      WRITE (2,109)
109    FORMAT(1H0//23H AVERAGED PLOT FOLLOWS )
      ITOT = ITOT + IAV(1) + IAV(2) + IAV(127) + IAV(128)
      IF(NDC.EQ.0) WRITE (2,106) ITOT,IMAX
      IF(NDC.EQ.1) WRITE (2,107) ITOT,IMAX
106    FORMAT(12H1LINEAR PLOT,//13H TOTAL CTS = ,I8,5X,
15HMAX = ,I7)

```

```

15HMAX = ,I7)
107 FORMAT(9H1LOG PLOT, //13H TOTAL CTS = ,I8,5X,5HMAX = ,I7)
IF(NDC.EQ.0) WRITE(2,106) JTOT,IMAX
IF(NDC.EQ.1) WRITE(2,107) JTOT,IMAX
20 DO 3 J = 1,128
IF(IND.EQ.1) CALL PLT (CP,IAV(J),NDC)
MT(J) = MT(J) + IAV(J)
3 CONTINUE
1 CONTINUE
JTOT = 0
DO 5 J=1,128
JTOT = JTOT + MT(J)
5 IMAX = MAX0(MAX,MT(J))
IF(NDC.EQ.0) CP = FLOAT(IMAX)/120.
IF(NDC.EQ.1) CP = ALOG(FLOAT(IMAX))/120.
WRITE(2,110)
110 FORMAT(36H0THIS IS THE TOTAL MASS DISTRIBUTION
119H FOR 120 TO 215 MEV )
IF(NDC.EQ.0) CP=FLOAT(IMAX)/120.
IF(NDC.EQ.1) CP=ALOG(FLOAT(IMAX))/120.
DO 6 J=1,128
6 CALL PLT(CP,MT(J),NDC)
RETURN
STOP
END

```

```

C      FILE PTEM2
C      CONTINUATION OF PTEM
C
      SUBROUTINE PTEM2
      DIMENSION IES(34)
      COMMON /ALPHA/ IDAT(1024),ICON(20,128),FN(2)
      COMMON /BETA/ P(120)
      COMMON /ZETA/ IAV(129),IND,NDC
      DO 200 J=3,123,4
      MASS = 50 + J
      If(IND.EQ.1) WRITE(2,249)
249    FORMAT(1H1)
      WRITE(2,250)
250    FORMAT(43H0THIS IS A PLOT OF AVERAGED DATA ABOUT MASS ,I4
1,2X,35HFROM 120 to 215 MEV IN 5 MEV STEPS )
      IMAX = 0
      DO 201 I=1,20
      FAV=FLOAT(ICON(I,J-2)+ICON(I,J-1)*2+ICON(I,J)*3
1+ICON(I,J+1)*2+ICON(I,J+2))/9.
      IES(I) = FAV + 0.5
      IMAX = MAX0(IMAX,IES(I))
201    CONTINUE
      CP = FLOAT(IMAX)/120.
      ITOT = 0
      ITOT1 = 0
      DO 202 I=1,20
      IF(IND.NE.1) GO TO 11
      WRITE(2,300)
300    FORMAT(1H0)
      CALL PLT2(CP,IES(I),0)
C
C      SUBROUTINE PLT2 IS IDENTICAL TO PLT
C      THE NAME WAS CHANGED TO FACILITATE CHAINING THE PROGRAM
C
11    ITOT = ITOT + IES(I)*I
      ITOT1 = ITOT1 + IES(I)
202    CONTINUE
      D = FLOAT(ITOT1)
      AMEAN = FLOAT(ITOT)/D
      D1 = 0
      SD2 = 0
      DO 400 I=1,20
      D1 = D1 + 1.00
400    SD2 = SD2 + FLOAT(IES(I))*((AMEAN-D1)**2)
      SD2 = SD2*25./(D-1.0)
      AMEAN = 115. + 5.*AMEAN
      WRITE(2,302) AMEAN,SD2
302    FORMAT(8H MEAN = ,F9.2,5X,11HVARIANCE = ,F9.3//)
200    CONTINUE
      WRITE (1,108)

```



```
108  FORMAT(16H 1=DO PTEM AGAIN  )  
      RETURN  
      STOP  
      END
```

```

C      FILE W20128
C      WRITING A 20 X 128 ARRAY ON TAPE
C      SUBROUTINE W20128 FOR CON
C
      SUBROUTINE W20128
      DIMENSION FILE(2)
      COMMON /ALPHA/ IC(1024),IDAT(20,128),FN(2)
1      WRITE (1,101)
101     FORMAT (32H FILE NAME FOR W20128 (A9) .DAT3 )
      READ (1,102) FILE(1),FILE(2)
102     FORMAT (A5,A4)
      CALL FSTAT(3,FILE,N)
      IF(N.EQ.-1) GO TO 500
      PAUSE 3
      CALL ENTER (3,FILE)
      DO 10 I=1,20
10      WRITE (3) (IDAT(I,J),J=1,128)
      CALL CLOSE (3,FILE)
      RETURN
500     WRITE (1,103)
103     FORMAT(21H FILE ALREADY ON TAPE )
      GO TO 1
      STOP
      END

```

```

C      SUBROUTINE FOR READING TAPES WRITTEN BY W20128
C
      SUBROUTINE R20128
      COMMON /ALPHA/ IDAT(21,128),FN(2)
1      WRITE (1,101)
101     FORMAT(15H FILE NAME (A9) )
      READ (1,102) FN(1),FN(2)
102     FORMAT (A5,A4)
      CALL FSTAT(3,FN,K)
      IF (K.NE.-1) GO TO 1000
      CALL SEEK (3,FN)
      DO 10 I=1,20
10      READ (3) (IDAT(I,J),J=1,128)
      DO 19 J=1,128
19      IDAT(21,J) = 0
      DO 20 J=1,128
      DO 21 I=1,20
21      IDAT(21,J) = IDAT(21,J) + IDAT(I,J)
20      CONTINUE
      RETURN
1000    WRITE (1,103)
103     FORMAT(24H FILE NOT FOUND ON .DAT3 )
      GO TO 1
      STOP
      END

```

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FRAGMENT ENERGY CORRELATIONS IN THE FISSION
OF ^{231}Pa BY 11.5-MeV PROTONS

by

CLIFFORD WARREN WOODS

B. S., Southern Oregon College, 1969

AN ABSTRACT OF A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

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Manhattan, Kansas

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Fragments from the 11.5-MeV proton induced fission of ^{231}Pa were observed with silicon surface barrier detectors. The data were analyzed by a mass-dependent energy calibration based on the observation of the fragments from the spontaneous fission of ^{252}Cf and the 11.5-MeV proton induced fission of ^{232}Th .

The results indicate a symmetric peak in yield at lower total kinetic energy of the fragments similar to that seen by Schmitt, Plasil, and Ferguson in 1969 for the proton induced fission of ^{232}Th . The increase observed in the variance of the total kinetic energy for symmetric fission has not previously been observed for other cases of fission.