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MODIFICATION AND FURTHER DEVELOPMENT OF THE
NUCLEON TRANSPORT CODE, NTC

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MASTER

Abstract

Several modifications to the Nucleon Transport Code NTC are described. Also, descriptions are provided for a few portions of the code which had previously been undocumented. Included in the report are the following:

1. The description of PREP, a data preparation routine,
2. A generalized framework for the High-Energy Analysis Program which handles the bookkeeping details and leaves the specialization to a particular problem to a few user-written routines,
3. A listing of improvements made in the treatment of evaporation processes,
4. The replacement of an older and incompletely documented version of O5R by the published version,
5. The description of a general-purpose evaporation model program in O5R to treat inelastic scattering,
6. The preparation of a special version of NTC using a straightahead approximation.

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Fig

I. Introduction

This report describes several modifications which have been made to the Nucleon Transport Code, NTC.¹ These include:

1. The writing of a generalized framework for the analysis section to handle the mechanics of reading the history tape, treating the evaporation part of the nuclear reactions, and linking with the O5R program for handling neutrons below the cut-off energy. The user now need write only a few subroutines to apply the code to a particular problem.
2. The modification of a few subroutines to provide automatic linkage of the published version of O5R² to NTC. This will eliminate the older and incompletely documented O5R version presently distributed with NTC. This also includes a general-purpose inelastic routine incorporating a version of Dresner's evaporation program³ to handle the inelastic scattering in O5R.
3. Improvements made in the treatment of evaporation processes with the inclusion of new data and with provision for the recoil of the residual nucleus.
4. The preparation of a special version of NTC to use a straight-ahead approximation.

This report will not describe any subroutine which is covered by either the NTC report¹ or the O5R² report. In fact, we will assume that the reader is familiar with both these documents and shall limit the descriptions given here to modifications made in the routines contained in these reports and previously distributed by RSIC.

¹ W. E. Kinney, The Nucleon Transport Code, NTC, ORNL-3610 (Aug. 1964).

² R. R. Coveyou, D. C. Irving et al., O5R, A General-Purpose Monte Carlo Neutron Transport Code, ORNL-3622 (Feb. 1965).

³ L. Dresner, EVAP, A FORTRAN Program for Calculating the Evaporation of Various Particles from Excited Compound Nuclei, CF 61-12-30 (1961).

The NTC system consists of:

1. PREP - a separate program which prepares a data tape needed by NTC.
2. High-Energy Transport Program
 - Chain 1 - reads NTC input and sets up some data tables.
 - Chain 2 - transports nucleons above a cut-off energy and calculates intranuclear cascades.
3. High-Energy Analysis Program
 - Chain 3 - provides for the evaporation part of nuclear reactions, transports protons below the cut-off, and analyzes the results of the transport above the cut-off.
 - Chain 4 - performs some summation and edit operations.
4. XSECT - a separate program which prepares cross-section data for O5R.
5. O5R - transports neutrons below the cut-off energy.
6. O5R Analysis - a separate program which analyzes the results of the O5R neutron transport.
7. EDIT - a separate program to combine the results of the NTC and O5R analyses and print out the final answers.

Section II through VIII of this report describe, in turn, the modifications made to each of these parts of the NTC system. Sections IX to XII deal with a few additional topics. Section XIII describes the sample problem. It is a revision of the sample problem description in the NTC report.

II. PREP Description

Since PREP was not covered in ORNL-3610, we have included the following description.

1. Bertini Data Tape must be Logical 8 on Drive B8; POOL, Log. 1 on A5. (In the version distributed by RSIC, the Bertini tape is logical 8 on B1, the pool tape is logical 4 on A4.)
2. Include Subroutines, "COPY," "READ," "WRITE," and "NOWRI" (FAP).

3. Deck Setup:

1. Control Cards - with tapes assigned as noted above (10, Input)
(9, Output)
2. Main Program
3. Subroutines "CØPY," "READ," "WRITE," and "NØWRI"
4. * DATA Card
5. WEK Data Cards

4. Operation:

1. The MAIN program first calls "CØPY," which, by successively calling "READ" and "WRITE," transfers 10 records from the Bertini Tape on B8 to the pool tape on A5. "CØPY," "READ," "WRITE," and "NØWRI" are described below.
2. The MAIN Program then reads the WEK data cards, computes the appropriate tables therefrom, and writes this information on the pool tape on A5, followed by an end-of-file. This completes the tape preparation operation.

5. Subroutines:

1. CØPY. This subroutine successively calls "READ" and "WRITE" as follows: CALL READ, RXX----where RXX is a symbol identifying the appropriate IØCT command needed by "READ," e.g.,

$$RXX \text{ IØCT STØR, } 0, 601$$
 where STØR is the initial address of a temporary storage area, and the number 601 indicates the current record length. CALL WRITE, RXX, START----where RXX is as above (IØCT command for "WRITE") and START is the error return address (see below).
2. READ. This subroutine makes 10 attempts to read a given record, returns to "CØPY" after a successful read, or calls "ERRØR" if all 10 attempts fail.
3. WRITE. This subroutine makes 10 attempts to write a given record, returns to "CØPY" after a successful write, or calls "NØWRI" (see below) if all 10 attempts fail. After calling "NØWRI," the order "HTR * 2,4" is executed. At this stop, the operator is instructed, via the on-line printer, to replace

the pool tape, logical 1 on A5 and then depress the start button. Control is then transferred to "START," the address in "COPY" where the copying of the Bertini tape commences.

4. ~~N~~OWRI. This subroutine rewinds logical 1 and logical 8, and then prints an on-line message to the operator:

"TAPE A5 is BAD. REPLACE IT AND HIT START."

Control then returns to the HTR order in "WRITE," above.

We have made no changes in this program from earlier versions. However, the input data has been modified following the suggestions of Peelle and Aebersold.⁴ These modifications supply values for various tables which had originally been set to 0 for Z or A less than 10. This should improve the treatment of very light nuclei. In addition, the table of experimental excess masses has been expanded to include additional values measured recently.

The changes are as follows:

	Card Number
First 10 values of CAM2 changed from 0 to Peelle-Aebersold data	3
First 10 values of CAM3 changed from 0 to Peelle-Aebersold data	13
First 5 even values of CAM4 changed from 0 to Peelle-Aebersold data	28
First 5 even values of CAM5 changed from 0 to Peelle-Aebersold data	33
Oxygen excess mass set at .000001	7
40 new values for excess mass, suggested by Peelle-Aebersold, were added to the end of the deck	between 151 and 152

A listing of the revised cards follows:

⁴R. W. Peelle and P. M. Aebersold, Energy Parameters for Light Nuclides in Monte Carlo Nuclear Evaporation Programs Based on EVAP, ORNL TM-1538 (1966).

29.2	19.2	24.2	20.9	23.1	18.0	19.5	16.9	19.7	17.1	18.2	15.0	16.0	12.04	3
18.3	15.9	11.5	14.3	11.6	15.9	13.9	16.0	12.1	13.9	12.2	14.4	13.1	15.8	13
540	280	330	270	190	210	213	154	142	151	173	144	14528		
600	280	320	300	170	170	217	174	175	172	163	141	12933		
15	6	13.1870	15	7	4.5280	15	8	7.2330	16	7	10.4020	16	8	0.000001 007
4	1	28.387	4	3	28.422	5	1	33.054	5	4	33.707	16	6	24.183
6	1	49.422	6	4	20.274	7	2	28.127	7	5	29.959	16	9	15.635
9	2	34.774	8	6	38.044	9	3	28.059	9	6	32.311	16	10	35.052
11	4	23.411	11	7	28.863	12	4	25.278	12	8	36.148	17	6	33.550
13	5	20.393	13	8	26.715	14	5	27.231	15	9	22.068	17	10	21.720
20	12	29.957	20	8	15.087	19	11	18.572	18	11	37.005	17	11	47.637
21	9	6.202	21	12	17.624	22	12	6.692	23	13	14.276	24	14	18.361
25	14	11.229	26	11	7.944	26	14	.896	26	15	24.813	24	10	1.122

III. High-Energy Transport Program

We have made no changes to this program.

Chain 2 has several versions, depending on whether or not collision records are written for a boundary crossing, escape, or slowing below EMIN for primary particles and whether or not scattering due to multiple Coulomb interactions is included. Comment cards inserted in the main program delineate the changes that must be made to convert from one version to the other. The routine distributed by RSIC allows for primary collision records and no Coulomb scattering. Reference is made in the comments to Coulomb cards 1 to 10 necessary to convert the program, but these have not been included in the distributed code. The Coulomb cards are:

```

C   COULOMB CARDS 1 THRU 7.
      IF (TIP(NB)) 1020, 1020, 1921
1921 IF (NAME(NB)=1) 1020, 1010, 1020
1010 CALLSPREAD(ARG(MAT), NOCAS, NAME(NB), E(NB), SSQ(NB),
      IU(NB), V(NB), W(NB), X(NB), Y(NB), Z(NB), WT(NB), THET(NB),
      2NMED(NB), D, EC(NB), SSQC(NB), UC, VC, WC, XC(NB),
      3YC(NB), ZC(NB), BLZ(NB), IND)
      IF (IND) 2001, 101, 140
C   COULOMB CARDS 8 AND 9.
152 IF (NAME=1) 155, 156, 155
156 IF (TIP) 155, 155, 157
C   PRIMARY COULOMB STATEMENT 155.
155 E(NB)=ESAVE
C   COULOMB CARDS 10 THRU 17.
      IF (NAME(NB)=1) 1021, 1030, 1021
1030 SSSS=SORTF(SSQC(NB))
      RT=SORTF(UC**2+VC**2)
      COSPHI=WC/SSSS
      SINPHI=RT/SSSS
      COSTH=UC/RT
      SINTH=VC/RT
      GOTO 1022

```

IV. High-Energy Analysis Program

A. Chains 3 and 4 as described in the NTC report have been combined into a new chain 3. This chain 3 has been modified to provide the framework for a fairly general analysis with a few routines left for the user to write. The earlier restriction to infinite slab geometry has been removed. The previous chain 5 has become chain 4 and is left for the user to write.

The "Analysis I" subroutine mentioned is named ANAL and provides the analysis for the nucleons above the cut-off energy. "Analysis II" is named ANAL2 and provides analysis for protons which are below the cut-off energy. In addition, a third subroutine, ANAL3, is required to analyze the energy available to particles with mass greater than 1.

The main program in chain 3 has one input card, format (2I10), containing NREC, the number of input cards from the GEOM input to the end of the chain 3 input, and NRECL, the number of chain 3 input cards which are also needed by chain 4. NREC and NRECL are used to hunt back on the input tape in running successive batches. Subroutines ANAL, ANAL2, and ANAL3 may require additional input cards.

The general flow chart of the High-Energy Analysis Code presented on page 9 of the NTC report remains valid. A more detailed flow chart for the main program of chain 3 is included here (see succeeding pages).

Chain 3. NTC Analysis - Main Program

B. Several modifications have been made to WEK, the subroutine which treats evaporation processes:

EREC, the recoil energy of the nucleus, has been added to the calling sequence.

The array NFINUC (70,35) was omitted (it was left out of the dimension statement, cards 073, 074, and 075).

A RETURN is put just before statement 701. This skips a dummy call to the main part of the program on the initialization call.

Statements 9 through 72 (cards 164-169), dealing with NFINUC, are omitted. The statement preceding 9 is changed from IF(SIGMA) 9, 9, 10 to IF(SIGMA) 30, 30, 10.

The following is inserted between cards 194 and 195:

```

      TEMPU = U-EP5-Q(JEMISS)
      IF(TEMPU) 20,20,2020
2020  U = TEMPU
      TOTE = EPS + EREC
      EPS = FLA(JEMISS)/A*EREC + (A-FLA(JEMISS))/A*EPS
      EREC = TOTE-EP

```

The present statement numbered 74 is removed and the succeeding statement (card 199) is labelled number 74. These changes deal with calculating the recoil energy of the residual nucleus and truncating the evaporation spectrum at the maximum available energy.

The following is inserted between cards 200 and 204:

```

      IF(JA-8) 223, 1223, 223
      IF(JZ-4) 223, 1224, 223
1224  SMOML(6) = SMOML(6) + U + .093 + EREC
      U = 0.
      EREC = 0.
      GO TO 30

```

This insertion deals with splitting ⁸Be into two alphas and assigns all the energy to emitted alpha energy.

The meaning of SOCHPE has been changed to be the total energy of all the particles emitted except protons and neutrons (previously the proton energy had been included), i.e., SMOML(2) is omitted from the summation on card 2042.

C. Subroutines ANAL, ANAL2, and ANAL3 must be written by the user and tailored to suit his particular problem. The collision data, the range-energy tables, and other data are located in COMMON and may be used by these routines. Subroutines ERNG, RANG, ERNLØ, and RNGLØ (described in Part D), which get data from the range-energy tables, and the random number package are also available for use.

The calling sequences for ANAL, ANAL2, and ANAL3 are:

ANAL (KEY)

where

KEY =	{	-1 Initialization at start of first batch
		-2 Initialization at start of each batch after the first
		-3 End of batch marker
		-4 End of run marker
		1 Normal call to ANAL to analyze the collision data

ANAL must read the NABØV record if one is present.

ANAL2 (KEY, E, SPDSQ, U, V, W)

where

KEY =	{	-1 Initialization at start of first batch
		-2 Initialization at start of each batch after the first
		-3 End of batch call
		-4 End of run call
		1 Analyze a proton which has slowed below cutoff
		2 Analyze a proton from the NLØ record
		3 Analyze a proton emitted in the evaporation process

E = energy of proton,

SPDSQ = speed squared,

U = x-component of velocity,

V = y-component of velocity,

W = z-component of velocity.

ANAL3 (KEY, HEVSUM, UU, EREC)

where KEY has the same meanings as for ANAL except that ANAL3 is to analyze HEVSUM, the sum of the energies of evaporated heavy charged particles, UU, the excitation energy of the residual nucleus and EREC, the recoil energy of the residual nucleus.

D. Four subroutines generally used by ANAL and ANAL2 have been included in the package as follows:

RANG (M, EY, R). Given the energy, RANG gets the range to EMIN from the range tables, where M = medium number, EY = energy ($E_{MAX} \geq EY \geq E_{MIN}$), and R = range from EY to EMIN.

ERNG (M, R, EN). Given the range to EMIN, ERNG gets the energy from the inverse range tables, where M = medium number, R = range to EMIN, and EN = energy corresponding to given range.

RNGLØ (M, EY, R). Given the energy, RNGLØ gets the range to 10 MeV from the low-energy range tables, where M = medium number, EY = energy ($E_{MIN} \geq EY \geq 10 \text{ MeV}$), and R = range from EY to 10 MeV.

ERNLØ (M, R, EN). Given the range to 10 MeV, ERNLØ gets the energy from the low-energy inverse range tables, where M = medium number, R = range to 10 MeV, and EN = energy corresponding to the given range.

E. Data concerning neutrons with energies below EMIN are written on logical tape 8, which then serves as input to the O5R source subroutine. This tape contains a sequence of 11 word records consisting of:

1. NEUTNØ - numbers the neutrons from 1 to the end of the batch,
2. E - energy, in eV,
3. S - speed, in cm/sec,
4. U
5. V velocity components, in cm/sec,
6. W
7. X
8. Y position coordinates,
9. Z
10. WT - neutron weight.

A record containing $NEUTN\emptyset = -1$ marks the end of each batch. An end-of-file follows the end of batch marker for the last batch.

F. Following the end of the last batch, Chain 4 will be called. If no information concerning the neutron histories below EMIN is needed, Chain 4 can be the final EDIT code, summing the NTC results and printing out the final answers. If, however, the O5R results are needed, the EDIT must be postponed and Chain 4 can be a dummy routine terminating the run with a CALL EXIT statement. We have found it useful, especially while debugging, to provide a simple routine for Chain 4 which will sum the NTC results and print out the preliminary data.

V. XSECT

No modifications have been made in the XSECT program as published in ORNL-3622.

VI. O5R

In using the published version of O5R in NTC, it was necessary to modify a few programs. These modifications are described below. In addition, a general-purpose program to treat inelastic scattering was formed by altering the evaporation model program of Dresner.³ This eliminates the need for the user to supply a KINNY routine for inelastic scattering.

It is not possible to run this O5R and the High-Energy Transport and Analysis routines consecutively as a single job using the chain feature due to an unfortunate incompatibility. O5R uses tapes 5 and 6 as input and output while the high-energy codes use tapes 9 and 10 as input and output and make another use of logical tape 6.

A. Subroutine GETNC. Subroutine GETNC was modified from the standard O5R to allow a neutron energy greater than the top energy of the supergroup. When this occurs the subgroup number is set to 1 and a printout is made of the neutron energy and the supergroup top energy (in MeV). This modification was necessary because the mechanics of NTC make it possible for an occasional O5R neutron to have an energy above 77.13 MeV. The correction effectively makes the cross sections go as $1/v$ above 77.13 MeV, but such occurrences are rare and no appreciable error is made in the final result.

<u>Original Statement</u>	<u>Modified Coding</u>
IF (NINC) 4, 5, 6	IF (NINC) 14,5,6
	14 ENERQ = SPDSQ/1.913220092E+18
	GRPTP = 2.0 * EGROUQ/ 1.913220092E+18
	WRITE OUTPUT TAPE 6, 15, ENERQ, GRPTP
	15 FØRQAT(13HOENERQY ERRØR, 2E20.8)
	GØ TØ 5

B. Subroutines MSOUR and SOURCE. O5R subroutine MSOUR has been modified to read the neutron source tape prepared by NTC and set up the source neutrons without calling a subroutine SOURCE. This MSOUR requires a single input card, format (I5), containing the logical tape number for the neutron source tape. This card should follow the O5R and GEOM input but precede the INELAS input. Cards G and H of the O5R input, which normally contain information pertaining to the source neutrons, will be ignored.

The position and weight of the source neutrons are read from the source tape. The energy specified on the source tape is converted to speed squared nonrelativistically and the velocity components are normalized to this value of speed squared. The neutron NAME is set to the neutron number on the NTC source tape.

This version of MSØUR is set up to aid in correlating the results from a neutron history with the NTC batch in which the neutron source was generated. Since a single batch in NTC may generate more neutrons than can be accommodated at one time in the O5R neutron bank, it may be necessary to break the NTC batch into several O5R batches. MSØUR reads the neutron source tape until either NSTRT sources have been generated or until the NTC end of batch marker (a negative neutron number) is encountered. If NSTRT sources are generated, UNUSED(1) is set to 0 as a signal that the end of the NTC batch has not been reached and ITERS is increased by one to keep the count in terms of O5R batches correct. When the NTC end of batch marker is reached, UNUSED(1) is set to 1 and ITERS is left unchanged. This procedure assumes that the value of NITS on the O5R input

card is the number of NTC batches processed and that NSTRT denotes the number of neutrons to be run in an O5R batch and need bear no relationship to the number of neutrons generated in any NTC batch. It also assumes that the BANKR subroutine is making use of the UNUSED(1) signal to accumulate results for several O5R batches and does not consider that the end of a batch has been reached unless $\text{UNUSED}(1) = 1$.

Subroutine S~~OUR~~CE, which was previously written by the user, has been eliminated.

C. Subroutine BANKR. In conjunction with the above modifications to MS~~OUR~~, a change has been made in subroutine BANKR to delay the end of batch signal until $\text{UNUSED}(1) = 1$.

Original Statement	Modified Coding
105 DO 1051 N1=NBCNT,NBMAX	105 IF ($\text{UNUSED}(1)-1$)81,1053,81
	1053 DO 1051 N1=NBCNT,NBMAX

D. Subroutines INELAS and KINNY. A general-purpose version of INELAS (see flowchart) has been written to accomplish inelastic scattering by calling BOIL, a version of Dresner's evaporation model code.³ The input data (follows O5R, GEOM, and MS~~OUR~~ input data) are as follows:

Card A_m: Format (2I5)

- a. MXEL(M) - number of inelastic scatterers in medium M
- b. LD (M) - number of elastic scatterers in medium M

Card B_{m,k}: Format (3E10.0,I10)

- a. ZNØ(K,M) - atomic number of compound nucleus
 - b. ANO(K,M) - mass number of compound nucleus
 - c. BIND(K,M) - binding energy gained by absorbing a neutron
 - d. NDIA(K,M) - number of binding energy diamond to use (see below)
- for Kth
inelastic
scatterer
in medium
M

K runs from 1 to MXEL (M) in the order in which the inelastic scatterers are arranged on the systems data tape.

Card C: Format (I5)

NUMDIA - the number of binding energy diamonds to be read in

Flowchart of INELAS

Card D: Format (E5.0,I5,E5.0,I5)

a. AINISH(M) - highest A value	} For M th binding
energy diamond
b. MXA(M) - number of A values	
c. ZINISH(M) - highest Z value	
d. MXZ(M) - number of Z values	

Card E_{j,m}: Format (2E15,5)

a. B _{j,m} : binding energy	} of the J th nucleus
b. DEL _{j,m} : pairing energy	

J denotes the (Z,A) of the nucleus in the order (ZINISH,AINISH), (ZINISH,AINISH - 1),..., (ZINISH, AINISH - MXA + 1), (ZINISH - 1, AINISH - 1),..., (ZINISH - 1, AINISH - MXA), (ZINISH - 2, AINISH - 2),..., (ZINISH - MXZ + 1, AINISH - MXA - MXZ + 2).

The input cards appear in the order:

(Card A_m, (Card B_{m,k}, K = 1, MXEL (M)), M = 1, MEDIA),
Card C, (Card D_m, (Card E_{j,m}, J = 1, MXA (M) * MXZ (M)),
M = 1, NUMDIA)

Present dimension statements allow:

NUMDIA ≤ 4
MXA (M) * MXZ (M) ≤ 121

INELAS operates by making successive calls to BOIL until no further particles are emitted. If no neutrons are emitted, the neutron weight is set to zero, thereby killing the incident neutron. If more than one neutron is emitted, additional neutrons will be created with a new NAME and with NAMEX (daughter) = NAME (parent). BANKR (9) will be called, creating a pseudo-collision with NCOLL = 9 to mark the birth of a new neutron. An error message is written on the output tape and a stop occurs if there is no room left in the neutron bank for a new neutron. The neutron velocities are chosen from an isotropic distribution. The energies and rem doses for emitted protons and alpha particles are recorded separately.

The recoil energy of the residual nucleus is computed using the so-called "90 degree" approximation. The recoil energy of the initial compound nucleus is calculated and subtracted from the excitation energy before BOIL is called. Thereafter, following the emission of each particle, the energy of emission (assumed to refer to the rest frame of the compound nucleus) is converted to the laboratory system using the assumption that the current recoil and emission directions are uncorrelated or perpendicular. The new recoil energy is computed likewise. When no further particles can be emitted the remaining recoil energy and the rem dose corresponding to it are recorded. The residual excitation energy is likewise recorded.

INELAS uses the UNUSED array to communicate the charged-particle energies to other subroutines as follows:

- UNUSED (2) - emitted proton energy, in MeV
- UNUSED (3) - emitted alpha energy, in MeV
- UNUSED (4) - energy of recoiling nucleus, in MeV
- UNUSED (5) - rem dose of emitted protons
- UNUSED (6) - rem dose of emitted alphas
- UNUSED (7) - rem dose of recoiling nucleus
- UNUSED (8) - residual excitation energy, in MeV

Subroutine QUEUE is called to compute rem doses from energies for the various charged particles.

Whenever ^8Be is encountered as a compound nucleus, the entire energy (recoil, excitation, and binding) is recorded as the energy and dose of two alpha particles.

INELAS assumes that the systems data tape has been written such that all elastic scatterers in a medium precede the inelastic scatterers.

Subroutine KINNY, which was previously written by the user, has been eliminated.

E. Obtaining INELAS Input Data. The data required by INELAS is a list of binding and pairing energies for the nuclides in a certain "diamond" of (Z,A) values. Whenever possible, the binding energies should be obtained from experimentally determined values. The best list presently available has been published by Mattuch et al.⁵ For other nuclides, program CAMRON can be used. CAMRON will, in addition, give the pairing energies for all nuclides.

A single diamond may be used which will supply the data for several inelastic scatterers with neighboring (Z,A) values. There is no penalty for having more than enough information in a diamond as long as the dimension of 121 is not exceeded. Decks have been prepared for use with (1) oxygen, nitrogen, and/or carbon; (2) silicon and/or aluminum; (3) copper, nickel, cobalt, and/or iron; (4) lead; and (5) uranium.

Program CAMRON computes the binding energy and pairing energy of nuclide (Z,A) using the semi-empirical mass formula of Cameron.⁶ The input is as follows:

Input:

Card A: Format (4I5)

IA1: initial atomic mass

NØA: number of A values

IZ1: initial atomic number

NØZ: number of Z values

The run is terminated by either a blank card or by exhausting the input.

Binding and pairing energies are calculated for the "diamond" of nuclides $(IZ1, IA1)$, $(IZ1, IA1-1)$, $(IZ1, IA1-2)$, ... $(IZ1, IA1 - NØA+1)$, $(IZ1-1, IA1-1)$, $(IZ1-1, IA1-2)$, ... $(IZ1-1, IA1-NØA)$, $(IZ1-2, IA1-2)$, ... $(IZ1-NØZ+1, IA1-NØA-NØZ+2)$.

⁵ Mattuch, Thiele, and Wapstra, Nucl. Phys. 67, 1 (1965).

⁶ A. G. W. Cameron, "A Revised Semi-empirical Atomic Mass Formula," Can. J. Phys. 35, 1021 (1957).

For each (Z,A) value, the binding energy, pairing energy, A, and Z are both printed and punched out. The punched card format is compatible with the input format used in INELAS:

Punched output: Format (2E15.8, 40X, 2I5)

BE: binding energy

DEL: pairing energy

IA2: atomic mass

IZ1: atomic number

CAMRON requires GET, a FAP subroutine containing tables of the shell plus pairing correction and the pairing energy. CAMRON uses input tape 5, output tape 6, and punch tape 7.

Subroutine GET (IZ, SZ, NN, SN, DEL):

IZ: number of protons

SZ: shell plus pairing correction $S(Z) + P(Z)$ ⁶

NN: number of neutrons

SN: shell plus pairing correction $S(N) + P(N)$ ⁶

DEL: pairing energy $P(Z) + P(N)$ ⁷

GET will call ERROR if the limits of $IZ \leq 100$ or $NN \leq 150$ are exceeded.

The data in GET have been augmented by the suggested values of Peelle and Aebersold⁴ for light nuclei.

F. Subroutine QUEUE. Subroutine QUEUE (KIND, E, REM) supplies the rem dose, REM, for the absorption of energy E (MeV) by a particle of type KIND, where

KIND = 1 for a proton,

= 2 for an alpha particle,

= 3 for a nucleus heavier than an alpha.

The formulas used are:

Protons: The damage curve of Ref. 8 as fitted by H. S. Moran.

⁷A. G. W. Cameron, Can. J. Phys. 36, 1043 (1958).

⁸J. D. Turner et al., Health Phys. 10, 783 (64); see esp. Fig. 6, p. 791.

Rem dose = $\sqrt{E} \cdot (10.05 - .1453 \cdot E - 4.97 e^{-.8889 \cdot E}) \cdot 1.6 \times 10^{-8}$
for $E < 10$ MeV.

Rem dose = $43.5 \times 10^{-8} + (E-10.) \cdot 1.6 \times 10^{-8}$ for $E > 10$ MeV.

Alphas and heavy nuclei: A quality factor of 20.

G. BOIL, An Evaporation Model Subroutine. Subroutine BOIL (AINISH, ZINISH, MXA, MXZ, B, DEL, A, Z, U, KIND, EP):

AINISH } Highest values of A and Z in B and DEL tables.
ZINISH }

MXA } Number of A and Z values in B and DEL tables.
MXZ }

B - Table of binding energies (dimension 121).

DEL - Table of pairing energies (dimension 121).

A } A and Z of nucleus (integral values).
Z }

U - Excitation energy of nucleus (MeV).

KIND - Type of particle emitted:

-1 A or Z outside of tables

0 no particle emission

+1 neutron emitted

+2 proton emitted

+3 alpha emitted

EP - Energy of particle emitted (MeV).

Quantities AINISH, ZINISH, MXA, MXZ, B, DEL, A, Z, and U are supplied to BOIL by the calling program. BOIL returns KIND and EP and in addition A, Z, and U are changed to reflect the particle emission.

The B and DEL tables must contain the binding and pairing energies (in MeV), for the "diamond" of (Z,A) values:

(ZINISH, AINISH), (ZINISH, AINISH-1), ... (ZINISH, AINISH-MXA+1),
(ZINISH-1, AINISH-1), (ZINISH-1, AINISH-2), ... (ZINISH-1, AINISH-MXA),
... (ZINISH-MXZ, AINISH-MXZ), ... (ZINISH-MXZ+1, AINISH-MXA-MXZ+2)
in the order indicated.

BOIL is a stripped down version of Dresner's EVAP routine,³ allowing for the emission of neutrons, protons, and alpha particles from an excited nucleus according to the evaporation model. Emission of a particle will always follow if it is energetically possible ("energetically possible" means the excitation energy is greater than the sum of the binding energy needed, the pairing energy, and the Coulomb barrier). The routine was originally constructed from EVAP by reducing the types of emitted particles from 19 to 3 and by modifying the input and output modes of the program.

Two additional modifications have been made since then:

1. If an emission energy, chosen from the evaporation spectrum, would result in a negative residual excitation energy, it is rejected and a new emission energy is chosen.

2. If no particle emission is possible, a check is made to see if the excitation energy is greater than the neutron binding energy (i.e., pairing energy is neglected). If it is, a neutron is emitted. [This corrects a situation wherein the cross sections would indicate that neutron inelastic collisions were possible but BOIL would not allow neutron (or any other) emission and consequently absorption would occur.]

VII. O5R Analysis Program

In problems where the analysis is not very complicated, the analysis routine may be combined with O5R and the two programs run together as a single routine. This eliminates the need for collision tape reading and writing and results in a considerable time saving as well as simplifying the mechanics of running O5R. It is accomplished very easily by removing BANKR, the O5R subroutine which normally writes the collision tape, and replacing it with an analysis subroutine designed to perform the particular analysis desired. This analysis subroutine will have the following specifications:

SUBROUTINE BANKR (NBNK)

NBNK = -1 Initialization at start of run
 = -3 End of batch
 = -4 End of run
 = 1 Source pseudo-collision
 = 2 Normal collision
 = 3 Russian Roulette death
 = 4 Escape pseudo-collision
 = 5 Neutron split (parent)
 = 6 Neutron split (daughter)
 = 7 Medium boundary crossing
 = 8 Weight doubled by Russian R oulette
 = 9 New neutron is born in an (n,2n) reaction

Same as NCOLL
 on the colli-
 sion tape

For NBNK > 0, the collision parameters are located in COMMON with the following correspondance:

Collision parameter	O5R variable
1. NCOLL	NBNK
2. NAME	NAME
3. S_1^2	SPDSQ
4. U_1	U
5. V_1	V
6. W_1	W
7. X_1	X
8. Y_1	Y
9. Z_1	Z
10. WT_1	WATE
11. S_0	SPOLD
12. U_0	UOLD
13. V_0	VOLD
14. W_0	WOLD
15. X_0	XOLD
16. Y_0	YOLD
17. Z_0	ZOLD

Collision parameter	O5R variable
18. WT_0	$\phi LDWT$
19. THETM	THETM
20. PSIE	PSIE
21. ETA	ETA
22. NGR ϕ UP	NGR ϕ UP
23. LELEM	LELEM
24. NREG	NREG
25. NMED	NMED
26. NAMEX	NAMEX
27. WATEF	WATEF
28. BLZNT	BLZNT
29. BLZ ϕ N	BLZ ϕ N
30. λ	THETM*SQRTF (SP ϕ LD)
31. S_0	SQRTF (SP ϕ LD)
32. S_1	SQRTF (SPDSQ
33. ETATH	ETA*THETM
34. F ϕ NE	F ϕ NE
35. not used	
36. not used	

Any input needed may be read in when NBNK = -1. The data cards should be placed immediately following the GEOM data and preceding any data read in by MS ϕ UR or INELAS. The present input numbers on card I of the O5R input may be used for anything needed.

Output is best written out at the end of the run (NBNK = -4). With some restrictions GEOM will be available for use in analysis.

Note: On card I of the O5R input, you must specify at least one collision parameter. This prevents a division by zero in the O5R input routine, but is otherwise irrelevant.

VIII. EDIT Program

The final results are prepared by a separate edit program since it must combine the results of both the high-energy and the O5R analysis programs. The O5R results have been grouped by batches which correspond to the batches in the NTC run and not to any batching required by the size of the O5R neutron bank. Therefore the O5R data and the high-energy analysis data can be added together, batch by batch, and the results treated as independent samples in the calculation of standard deviations.

IX. Version of NTC for a Straightahead Approximation

Modifications have been made to the NTC-O5R routines to incorporate a straightahead approximation. To define the approximation as it is used here, we note that, in general

$$F_{ij} = F_{ij}(E', E, \vec{\Omega}', \vec{\Omega}) ,$$

where F_{ij} = the number of particles of type i per unit energy range per unit solid angle possessing kinetic energy E and direction $\vec{\Omega}$ after a particle of type j with kinetic energy E' and direction $\vec{\Omega}'$ undergoes either an elastic or a nonelastic collision. In the straightahead approximation we set

$$F_{ij} = f_{ij}(E', E) \frac{\delta(\vec{\Omega}' \cdot \vec{\Omega} - 1)}{2\pi} ,$$

where

$$f_{ij}(E', E) = \int_0^\pi \int_0^{2\pi} F_{ij}(E', E, \vec{\Omega}', \vec{\Omega}) d\vec{\Omega} .$$

In terms of the Monte Carlo calculation, what is done is to carry out the general calculation in the scattering subroutines, calculating all energies as if multidirectional scattering were occurring, and then to rotate the direction of all emergent particles to be identical with the direction of the incident particle.

The program changes necessary are as follows:

MAIN2 (The MAIN program in NTC chain 2)

Full Treatment

Straightahead Approx.

3rd, 4th, and 5th cards after Statement 252:

3rd:	$ALFB(NBEL\phi) = ALPHA(N) * C\phi SKS - BETA(N) * SINKS$	$ALFB(NBEL\phi) = 0.$
4th:	$BETAB(NBEL\phi) = BETA(N) * COSKS - ALPHA(N) * SINKS$	$BETAB(NBEL\phi) = 0.$
5th:	$GAMB(NBEL\phi) = GAM(N)$	$GAMB(NBEL\phi) = 1.$

5th, 6th, and 7th cards after Statement 253:

5th:	$WPP = SP * GAM(N)$	$WPP = SP$
6th:	$UPP = SP * (ALPHA(N) * C\phi SKS - BETA(N) * SINKS)$	$UPP = 0$
7th:	$VPP = SP * (BETA(N) * C\phi SKS + ALPHA(N) * SINKS)$	$VPP = 0$

MAIN3 (The MAIN program in NTC chain 3)

(2nd through 10th statements beyond statement 33)

$RT = SQRTF(U * V + V * V)$

$C\phi SPHI = W/S$

$SINPHI = RT/S$

$IF(RT) 2001, 2001, 2002$

These
statements completely
removed

2001 $C\phi STH = .73590$

$SINTH = .67709$

$G\phi T\phi 2003$

2002 $C\phi STH = U/RT$

$SINTH = V/RT$

(beginning at statement 102)

102 $WPP = SB * GAMR(N)$

$UPP = SB * ALFB(N)$

$VPP = SB * BETAB(N)$

$T1 = UPP * C\phi SPHI - WPP * SINPHI$

$UB = C\phi STH * T1 - SINTH * VPP$

$VB = SINTH * T1 + C\phi STH * VPP$

$WB = C\phi SPHI * WPP - SINPHI * UPP$

102 $SP1 = SB/S$

$UB = U * SP1$

$VB = V * SP1$

$WB = W * SP1$

Full Treatment

(beginning at the 3rd statement beyond 300)

CALL GTISØ (ALF, BET, GAMA)

S = SQRTF(SQNEUT)

104 UB = ALF *S

VB = BET *S

WB = GAM * S

(beginning at the 3rd statement beyond 400)

CALL GTISØ (ALF, BET, GAMA)

S = SQRTF (SQP)

UB = ALF *S

VB = BET *S

WB = GAM *S

05R Subroutines

SCATR

Straightahead Approx.

S = SQRTF(SQNEUT)

SP1 = SQRTF
(SQNEUT/SSQ)

UB = U *SP1

VB = V *SP1

WB = W *SP1

SP1 = SQRTF (SQP/SSQ)

UB = U *SP1

VB = V *SP1

WB = W *SP1

Insert following
statement 36:VDEG = SQRTF
(SPDSQ/SPØLD)

U = UØLD * VDEG

V = VØLD * VDEG

W = WØLD * VDEG

INELAS

(beginning at the second statement following 400)

SP = SQRTF (SPDSQ)

CALL GTISØ (UØ, VØ, WØ)

U = SP * UØ

V = SP * VØ

W = SP * WØ

VDEG = SQRTF
(SPDSQ/SPØLD)

U = UØLD * VDEG

V = VØLD * VDEG

W = WØLD * VDEG

X. List of Subroutines Contained in NTC

<u>Routine</u>	<u>Language</u>	<u>Function</u>
<u>PREP</u>		
PREP	Fortran	Prepares data tape by adding WEK data to BERT data.
COPY	Fap	Copies 19 records of BERT data to new tape.
READ	Fap	Reads 1 record.
WRITE	Fap	Writes 1 record.
NOWRI	Fap	Carries out an error procedure in case the BERT data cannot be written on the new tape.
<u>Chain 1</u>		
MAIN1	Fortran	Reads input, computes and stores cross sections, sets up range tables.
GTHSIG	Fortran	Given the energy and type of particle, finds the proton scattering cross section.
NPSIG	Fap	Sets the cross sections for n,p scattering at the energies which bracket E in GTHSIG; cross sections exist for every 10 MeV from zero.
PPSIG	Fap	Sets the p,p cross sections at the energies which bracket E in GTHSIG.
READ	Fap	Reads BERT data tape on channel A5 and picks off geometric cross sections for A = 1 to 239.
REDE	Fap	Carries out the tape reading operations for the BERT data.
RANGE	Fortran	Computes and stores range and inverse range tables.
INC	Fortran	Computes dx/dE at energy E for use in RANGE.
ZFOI	Fortran	Computes effective ionization potential.
<u>Chain 2</u>		
MAIN2	Fortran	Transports nucleons and writes history tape on logical tape 6.
JSET	Fap	Establishes the storage for the GEOM routine and calls JMIN to read the geometry specifications.
GMSOR	Fortran	Calls LOKZ for each source nucleon to set necessary quantities in GEOM.
GMPRP	Fortran	Sets up and calls GEOM for a particle flight to determine whether the nucleon has escaped from the region.

<u>Routine</u>	<u>Language</u>	<u>Function</u>
CASCAD	Fortran	Selects a target nucleus and calls the necessary routines to perform the nuclear interactions, or, in the case of hydrogen, the elastic scattering.
ECØL	Fortran	Given the range, computes the energy of a proton.
PSCAT	Fortran	Computes n,p and p,p elastic scattering.
RECØIL	Fortran	Computes recoil energy of residual nucleus.
SPDSQ	Fortran	Given an energy, computes the speed squared.
GTHSIG	Fap	Same as in Chain 1.
PPSIG	Fap	
NPSIG	Fap	
RANDØM Package	Fap	Selects random variables from various distributions.
GEØM Package	Fap	Geometry routine.
BERT	Fap	Performs intranuclear cascade calculation.
SØRT	Fortran	Reads BERT data from tape A5.
GTPRAM	Fortran	Selects and stores BERT parameters for required nuclei.
SØRS*	Fortran	Reads in source input data if first argument is 0 or provides data for a source particle if first argument is 1.
SPREAD**	Fortran	Computes Coulomb small-angle scattering.
GAURN**	Fortran	Picks from a Gaussian distribution.
<u>Chain 3</u>		
MAIN3	Fortran	Computes range-energy tables from 10 to EMIN; reads history tape; calls ANAL, ANAL 2, and ANAL 3 to perform analysis and put batch results on logical tape 7; calls WEK to treat evaporation part of nuclear interaction; puts 05R source neutrons on logical tape 8.
RANGE	Fortran	Same as in Chain 1.
INC	Fortran	
SKIP	Fap	Skips 19 records on A5 past BERT data to WEK data.

*Written by user.

**Used only in Coulomb scattering version of NTC.

<u>Routine</u>	<u>Language</u>	<u>Function</u>
WEK	Fortran	Evaporates particles from excited nuclei.
DØST	Fortran	Returns parameters needed by WEK.
ENERGY	Fortran	Returns either experimental or, if there is none, calculated binding energy for given A and Z.
WAPTB	Fortran	Fills in the gaps in the table of experimental binding energies with calculated values.
RANDØM Package	Fap	Same as in Chain 2.
RANG	Fortran	Given the energy, gets the range to EMIN.
ERNG	Fortran	Given the range to EMIN, gets the energy.
RNGLØ	Fortran	Given the energy, gets the range to 10 MeV.
ERNLØ	Fortran	Given the range to 10 MeV, gets the energy.
ANAL*	Fortran	Analyzes collisions and ionization above cutoff energy.
ANAL2*	Fortran	Analyzes proton slowing down below cutoff.
ANAL3*	Fortran	Analyzes heavy evaporated particles, nuclear recoils, and residual nuclear excitation.
<u>Chain 4</u>		
MAIN4*	Fortran	Produces preliminary results.

*Written by the user.

XI. List and Description of Quantities Stored in COMMON
for NTC Chains 1 Through 4

Position in COMMON	Quantity	Dimension	Description
1-85	DUMMY	85	Used by GEOM.
86	EMAX	1	See input specifications.
87	EMIN	1	See input specifications.
88	MXMAT	1	See input specifications.
89	MAXCAS	1	See input specifications.
90	NRAN	1	See input specifications.
91	MAXBCH	1	See input specifications.
92	NØBCH	1	Batch counter; set initially to 0; not used by Chain (1,3) or Chain (2,3).
93	DELER	1	Width of the uniform energy interval in the range tables; same for all media.
94-97	DENH(M)	4	See input specifications.
98-101	NEL(M)	4	See input specifications.
102-141	Z(I,M)	(10,4)	See input specifications.
142-181	A(I,M)	(10,4)	See input specifications.
182-221	EIØN(I,M)	(10,4)	Average ionization potential for the Ith element in the Mth medium; cal- culated by $\begin{aligned} EIØN &= 9.0 \times Z; & Z \geq 30; \\ &= Z[12.8 - 3.8(Z - 5)/25] & 5 \leq Z < 30; \\ &= 59.0, & Z = 4; \\ &= 34.5, & Z = 3; \\ &= 44., & Z = 2; \\ &= 17.5, & Z = 1. \end{aligned}$
222-261	DEN(I,M)	(10,4)	See input specifications.
262-265	SIGT(M)	4	Macroscopic geometric total cross section for medium M.
266-305	SIG(I,M)	(10,4)	Ratio of macroscopic geometric total cross section for Ith element in medium M to SIGT(M).
306-309	SIGH(M)	4	Ratio of hydrogen cross section to SIGT for medium M.

Table 1 (cont.)

Position in COMMON	Quantity	Dimension	Description
310	HSIGMX	1	Hydrogen n,p cross section at EMIN.
311-314	RNGMX(M)	4	Range at EMAX for medium M.
315-318	DELRNG(M)	4	Range interval in inverse-range tables for medium M.
319-722	RNGE(I,M)	(101,4)	Range tables: I = entry; M = medium.
723-1126	ER(I,M)	(101,4)	Inverse-range tables: I = entry; M = medium.
1127-1130	ARG(M)	4	Parameter used in Coulomb scattering calculations for medium M.
1131-1134	RNMXLØ(M)	4	Range from EMIN to 10 MeV in medium M.
1135-1138	DRNGLØ(M)	4	Range interval in low-energy inverse range tables for medium M.
1139-1542	RNGELØ(I,M)	(101,4)	Low-energy (50 to 100 MeV) range tables: I = entry; M = medium.
1543-1946	ERLØ(I,M)	(101,4)	Low-energy inverse range tables: I = entry; M = medium.
1947	YO	1	Data used by WEK, the evaporation routine.
1948	BO	1	Data used by WEK, the evaporation routine.
1949-1976	T	(4,7)	Data used by WEK, the evaporation routine.
1977-2106	CAM2	130	Data used by WEK, the evaporation routine.
2107-7306	WAPS	(250,20)	Data used by WEK, the evaporation routine.
7306	NØCAS	1	Current cascade number.
7308	NØØI.	1	Integer denoting type of event.
7309	NAME	1	Number of particle initiating this event.
7310	TIP	1	Type of particle.
7311	E	1	Energy of particle at birth.
7312	SSQ	1	Speed squared of particle at birth.
7313	U	1	Velocity of particle in x direction.

Table 1 (contd.)

Position in COMMON	Quantity	Dimension	Description
7314	V	1	Velocity of particle in y direction.
7315	W	1	Velocity of particle in z direction.
7316	X	1	Position coordinate of particle at birth.
7317	Y	1	Position coordinate of particle at birth.
7318	Z	1	Position coordinate of particle at birth.
7319	WT	1	Weight of particle.
7320	THET	1	Geometrical mean free flight time.
7321	XC	1	Position coordinate of the event.
7322	YC	1	Position coordinate of the event.
7323	ZC	1	Position coordinate of the event.
7324	EC	1	Energy of the particle at the start of the event.
7325	SSQC	1	Speed squared of the particle at the start of the event.
7326	NREG	1	Medium number in which the event occurred.
7327	NABØV	1	The number of cascade particles having energies above EMIN.
7328	NLØ	1	The number of cascade particles having energies below EMIN.
7329	ZPR	1	The charge number, Z, of the residual nucleus.
7330	APR	1	The mass number, A, of the residual nucleus.
7331	EX	1	The excitation energy of the residual nucleus.
7332	EREC	1	The recoil energy of the residual nucleus.

Common locations 1 - 1130 are reserved in all chains and remain untouched, by the overlays. Common locations 1131 - 7332 are reserved only in chain 3, and this data must be restored at the start of chain 3 each time it is entered.

XII. DUMCØL

A short routine, DUMCØL, has been written to print out the contents of a collision tape. It is frequently helpful when debugging the application of NTC to a particular problem. The input consists of a single card containing two integers N and M in the format (2I10), where

N = number of cascades to skip before printing, and

M = number of cascades to print (if M = 0, all cascades will be printed).

The collision tape is mounted as logical 6; the standard input and output are on logical 10 and 9, respectively. The collision data is printed out in the same order as on the collision tape. Blank lines separate records. The NABØV and NLØ records are identified as such.

XIII. SAMPLE PROBLEM

In the NTC and Ø5R reports it has been emphasized that the primary function of both programs are to produce particle histories which can be arbitrarily analyzed by the user. This flexibility may be more clearly demonstrated by an examination of a sample analysis routine written for a specific problem. It is hoped that this will illustrate the use of the program and will clarify any vague points which may exist in the descriptions. In addition the proper functioning of NTC in the hands of the user can be verified by running this problem and duplicating the results supplied.

The problem solved concerns the distribution in angle and energy of the neutrons and protons resulting from a beam of protons incident on an infinite slab of aluminum. The slab is 10-cm thick and is divided into four equal subslabs. Results are obtained for each subslab.

The initial protons are normally incident on the slab with an energy of 160 MeV. Two batches of 2000 protons each are used for the sample. A sample subroutine SORS is included in the package which will, with the sample data, generate the desired source for the sample problem.

The high-energy collision data is analyzed batch by batch in chain 3 by sample versions of ANAL, ANAL2, and ANAL3 and the results are written on a tape (logical 7). At the conclusion of the history generation and analysis, control passes to chain 4 (consisting of MAIN4, ANAL5, and ANAL25). Here tape 7 is read and the data generated by ANAL and ANAL2 are summed over batches, normalized, and various results are printed out. Standard deviations for all quantities are estimated from the variation of the batch results. ANAL data are treated by ANAL5 while that from ANAL2 is treated by ANAL25. The data from ANAL3 must be held until after the running of Ø5R so that the contribution from neutron histories below EMIN can be added in.

ANAL estimates the angular distributions of uniformly wide energy groups of nucleons escaping from the rear faces of as many as four infinite slabs which are integral subdivisions of the infinite slab for which the high-energy transport calculation was made. The uniform energy group

width is arbitrarily specified. The number of nucleons in each group is reported as a function of arbitrarily wide (not necessarily equal) intervals of the cosine of the angle between the normal to the slab and its rear face, in units of $\text{number} \cdot \text{MeV}^{-1} \cdot (\text{unit cosine})^{-1} \cdot (\text{incident source nucleon})^{-1}$. In addition, a summation over all angles is made to give an estimate of the energy spectrum of nucleons emerging from the rear face of each subslab. ANAL also permits study of the spread of the beam as it proceeds through a medium by estimating the variation with radius r of the fraction of particles emerging from the rear face of the slab within a circle of radius r centered at the intersection of the velocity vector of the primary beam with the slab face. Finally, an estimate of the number of neutrons with energies greater than EMIN emerging from the rear faces of the subslabs per incident source particle and an estimate of the total number of neutrons with energies greater than EMIN escaping from both front and rear faces of the subslabs per incident source particle are reported.

ANAL2 estimates the angular distributions of uniformly wide energy groups of protons having energies below EMIN within the subslabs, in the hope that distributions of such protons emerging from the slabs can be sufficiently well determined from these data. The proton angular flux is reported as a function of arbitrary intervals of the cosine of the angle between the normal to the slab and its face, in units of $\text{cm} \cdot \text{cm}^{-3} \cdot \text{MeV}^{-1} \cdot (\text{unit cosine})^{-1} \cdot (\text{incident source particle})^{-1}$. Integration over all angles gives the energy-dependent flux.

Input to ANAL

Card 1. Format $\begin{matrix} a & b & c & d \\ (E10.3, I10, I10, I10) \end{matrix}$

- a. T The slab thickness, in cm.
- b. NX The number of subslabs into which the infinite slab is to be divided; $NX \leq 4$. All quantities are computed at the rear for each subslab. For a 10-cm-thick slab and $NX = 4$, for example, the leakage spectra, angular distributions, etc., of nucleons emerging from 2.5-, 5.0-, 7.5-, and 10-cm-thick slabs will be computed.

- c. NR The number of radial boundaries for the computation of spreading; $NR \leq 16$. See below.
- d. NA The number of angular groups in the computation of angular distribution; $NA \leq 10$.

Card 2. Format (7E10.3)

FMU(I) The cosines of the lower limit of the angular groups with cosines in increasing order.

I=1,NA It is assumed that the upper limit of group 1 is 90°

Card 3. Format (7E10.3)

R(I) The upper boundaries of the Ith radial groups in increasing order.

I=1,NR The spreading is computed at each subslab and is reported as the fraction of the total number of particles emerging from the slabs lying within R.

Card 4. Format (E10.3,E10.3,I10)

- a. EHI The upper energy for the energy spectrum calculation, MeV.
- b. EL ϕ The lower energy for the energy spectrum calculation, MeV.
- c. NE The number of (equal) energy intervals between EHI and DL ϕ .

Input to ANAL2

Card 1. Format (I10,I10,I10,E10.3)

- a. NX The number of subslabs. See ANAL input.
- b. NE The number of energy groups below EMIN for the calculation of proton spectra; $NE \leq 5$.
- c. NA The number of angular groups in the computation of angular distribution; $NA \leq 10$.
- d. T The slab thickness, in cm.

Card 2. Format (7E10.3)

E(I) The lower-energy limit, in MeV, of the Ith group in descending order with EMIN as the upper limit for group 1.

Card 3. Format (7E10.3)

FMU(I) The cosine of the lower limit of the angular group.
I=1,NA Same as in Card 2 of ANAL input.

Input to ANAL3

Card 1: Format (E10.3,I10)

- a. XCAP Thickness of the infinite slab in cm.
- b. JMAX The total number of subslabs in which the energy deposited by particles with $A > 1$ and the residual excitation energy of the nucleus after evaporation are to be estimated.

NREC (in input to chain 3) must be the number of cards in the input to GEOM, SØRS, MAIN3, ANAL, ANAL2, and ANAL3 so that the input tape can be backspaced for each new batch. Subroutines ANAL5 and ANAL25 read the input data for ANAL and ANAL2 so NREC1 must equal the number of cards in the input to ANAL, ANAL2, and ANAL3. The NTC run will end with the ANAL3 input card not read.

The neutrons which appear with energies below EMIN are put on the Ø5R source tape and are transported by Ø5R until they leak from the system. The Ø5R Analysis Routine estimates the angular distributions of arbitrarily wide energy groups of neutrons having energies below EMIN which emerge from the rear faces of the subslabs mentioned in the description of ANAL. The number of neutrons, in units of $\text{number} \cdot \text{MeV}^{-1} \cdot (\text{unit cosine})^{-1}$ (high-energy source particle)⁻¹, is reported in the same format as the nucleon analysis of ANAL. The angular groups are summed over all angles to give an energy spectrum and, again as in ANAL, an estimate is made of neutrons emerging from the rear faces of the subslabs as well as of neutrons emerging from both front and rear faces of the subslabs, both normalized to unit incident high-energy source particle.

The ϕ 5R collision parameters are NC ϕ LL, NAME, X1, U ϕ , X ϕ , WT ϕ , λ , and SO, and the first collision tape is logical tape 9 (for sample problem).

The ϕ 5R analysis routine consists of a main program, ϕ ANL, and two subroutines ANL ϕ 5R and ANAL3 ϕ . ANL ϕ 5R performs the major analysis with ANAL3 ϕ merely recording on a tape the energy deposited by heavy particles and residual nuclei. Standard deviations for the neutron results were not calculated although they could have been estimated from the batch variation.

Input to ϕ 5R Analysis Code

Card 1. Format (I10,I10,E10.3,E10.3,F10,F10,E10.3)

- a. NX The number of subslabs into which the slab is subdivided (same as NX in ANAL input).
- b. NA The number of angular groups (same as NA in ANAL input).
- c. TLIM1 The upper-energy limit, in MeV, of the first major energy group for energy spectra calculation.
- d. TLIM2 The upper-energy limit, in MeV, of the second major energy group for energy spectra calculation.
- e. DL1 The energy group width, in MeV, of the minor energy groups in the first major energy group.
- f. DL2 The energy group width, in MeV, of the minor energy groups in the second major energy group.
- g. T ϕ T The total number of source nucleons, i.e., MAXCAS*MAXBCH, which gives rise to the neutrons in ϕ 5R. This value is used to normalize results to unit source strength.

The energy spectra are calculated for groups of width DL1 from 0 to TLIM1 and for groups of width DL2 from TLIM1 to TLIM2. The total number of energy groups must be equal to or less than 22.

Card 2. Format (7E10.3)

- FMU(I) The same quantity as FMU(I) in ANAL; I = 1,NA.

Card 3. Format (E10.3)

- T The thickness of the slab, in cm.

Card 4. Format (E10.3,I10)

- a. XCAP The same quantities as input to ANAL3
- b. JMAX

The operations needed to generate the sample result may be shortened by one step by combining the ϕ 5R and ϕ 5R analysis. To accomplish this, the general subroutine BANKR in ϕ 5R is replaced by a version of BANKR written for the sample problem and which calls subroutines ANL ϕ 5R and ANAL3 ϕ . In this case the history tape will not be written but the data will be analyzed as it is generated. The input to the ϕ 5R Analysis should be included with the ϕ 5R input following the GEOM input and before the source tape card.

The final operation is to combine the data from ANAL3 and from ANAL3 ϕ concerning the energy deposited by evaporated particles with $A > 1$ and recoiling nuclei and the residual excitation energy of nuclei after evaporation. This is done by the EDIT program using the tapes produced by the high energy and ϕ 5R analysis programs. The data is summed, normalized, and standard deviations are estimated. The results are given for equal subslabs of the infinite slab in units of $\text{MeV}\cdot\text{cm}^{-1}$. (incident source nucleon) $^{-1}$.

Input to EDIT

Card 1: Format (E10.3,4I10)

- a. XCAP Thickness of the infinite slab in cm.
- b. JMAX The number of subslabs in which the energy deposited by particles with $A > 1$ and the residual excitation energy are to be estimated.
- c. MAXBCH The number of batches in the NTC run.
- d. MAXCAS The number of source particles per batch in the NTC run.
- e. NREC The number of records of ANAL and ANAL2 data per batch on the tape 7 from NTC. $\text{NREC} = \text{NX} \cdot \text{NET} + 2$ where NX is the number of subslabs from the ANAL input and NET equals the sum of NE from card 4 of the ANAL input plus NE from card 1 of the ANAL2 input.

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