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IDENTIFICATION OF NUCLEAR REACTIONS REGISTERED IN IONOGRAPHIC DETECTORS

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PROGRAM SUMMARY

Title of program: JOTOV

Catalogue number: ABKF

Program obtainable form: Clc Program library, Queens' University of Belfast, N. Ireland (see application form in this issue)

Installation: DCT 2000 UNIVAC Terminal, Universidad Autónoma de Barcelona

Operating system: EXEC 8

Programming language used: FORTRAN IV

High speed storage required: 24 Kw.

Number of bits in a word: 36

Overlay structure: none

Number of magnetic tapes required: none

Other peripherals used: card reader, line printer, disc

Number of cards in combined program and test deck: 5278

Card punching code: BCD

Keywords: Nuclear, reaction, ionographic detector, experimental analysis, minimization, chi-square probability, intermediate energy, range-energy relation

Nature of physical problem
A nuclear reaction appears in a ionographic detector as an interaction star whose geometry can be accurately measured. Identity and energy of the incoming beam are known but the identity of the target and emergent prongs are not. Once a target has been assumed and a charge and mass number hypothesis (Z,A) has been made for each prong, the complete kinematics of the reaction can be established. All possible hyphtheses are examined under the requirements of conservation of momentum and total energy.

Method of solution
The chi-square function is minimized by the method of Lagrange multipliers, the conservation of momentum and energy giving the four constraints. This leads to a system of non-linear equations which are solved by an iterative procedure. Convergence of parameters and conservation values is tested during the resolution.

Typical running time
Typical CPU times for identification of one event in nuclear emulsion are:

Beam	Possible targets	Number of prongs	Time (sec)
Alpha	C,N,O	4	20
Alpha	C,N,O	5	45
Alpha	C,N,O	6	150
Proton	C,N,O	4	4
Proton	C,N,O	5	18
Proton	C,N,O	6	80
Proton	C,N,O	7	145

These times represent an average over a great number of events.

LONG WRITE-UP

1. Introduction

This work aims to identify nuclear reactions induced by intermediate energy beams on the nuclei of a ionographic detector such as nuclear emulsion or silver chloride crystals. The objects of our study are the interaction stars of any number of prongs registered in these detectors. Once the geometry of the interaction has been measured and a charge and mass hypothesis has been made for each prong, the range–energy relation for the particular detector allows the kinematics of the reaction be established [1–3]. Our program chooses the most likely kinematical configurations for a given event and assigns a statistical weight to each accepted hypothesis.

Our identification method is based on the same assumptions as the one used by the bubble chamber [4], but in our case the geometry of interactions is simpler (no track curvature) and the number of hypotheses to be examined for each event is much greater. Table 1 illustrates this statement. The number of hypotheses listed refer to those compatible with charge and mass number conservation.

2. Theory [5]

Let $x_1 \dots x_N$ be a set of N independent measured variables. Let $x_1^m, \dots x_N^m$ be the result of the physical measurement of these quantities and $\sigma_1 \dots \sigma_N$ the corresponding errors. The chi-square function is defined

$$\chi^2 = \sum_i (x_i - x_i^{\mathrm{m}})^2/\sigma_i^2 .$$

Table 1

Beam	Possible targets	Number of prongs	Number of hypotheses
Alpha	C,N,O	3	101
Alpha	C,N,O	4	913
Alpha	C,N,O	5	4469
Alpha	C,N,O	6	16291
Proton	C,N,O	3	67
Proton	C,N,O	4	396
Proton	C,N,O	5	1636

Let us suppose these N variables verify the k constraints

$$f_j(x_1 \dots x_N) = 0, \qquad j = 1, \dots k.$$

The solution $\bar{x}_1 \dots \bar{x}_N$ which makes chi-square a minimum and verifies the k constraints must be found by the method of Lagrange multipliers. The system of $N + k$ equations with $N + k$ unknowns, namely the $x_1 \dots x_N$ and the $\lambda_1 \dots \lambda_k$ arbitrary multipliers is non-linear on account of the non-linear character of the constraints. The solution is given by

$$\bar{X} = X^{\mathrm{m}} + \Delta X,$$

where matrix notation is now used and X stands for $x_1 \dots x_N$ as a column matrix.

If $\tilde{X}$ is an approximate solution, the correction ΔX to X^{m} is given by

$$\Delta X = -(G_x^{\mathrm{m}})^{-1} B^{\mathrm{T}} \lambda,$$

where

$$B = \partial F/\partial \tilde{X} \quad \text{and} \quad G_x^{\mathrm{m}} = \begin{bmatrix} 1/\sigma_1^2 & & \\ & \ddots & \\ & & 1/\sigma_N^2 \end{bmatrix},$$

$$\lambda = G_B R \qquad \text{and} \qquad G_B = (B(G_x^{\mathrm{m}})^{-1} B^{\mathrm{T}})^{-1},$$

$$R = F(\tilde{X}) - B\Delta\tilde{X}.$$

The covariance matrix for the x values is

$$G_x^{-1} = (\partial X/\partial X^{\mathrm{m}})\, (G_x^{\mathrm{m}})^{-1}\, (\partial X/\partial X^{\mathrm{m}})^{\mathrm{T}},$$

and after some algebra

$$G_x^{-1} = (G_x^{\mathrm{m}})^{-1} - ((G_x^{\mathrm{m}})^{-1} B^{\mathrm{T}})\, G_B^{-1}\, (B(G_x^{\mathrm{m}})^{-1}).$$

The solution $\bar{X}$ has been found by developing the constraints $F(X)$ in a power series up to first order in the neighbourhood of the approximate solution $\tilde{X}$. The final errors are given by the main diagonal of the matrix G_x^{-1}. This process is one step of an iteration procedure. The measured value X^{m} is taken as the initial approximate solution $\tilde{X}$ to start the first iteration.

3. Application to our problem

For an N prong interaction we have $3N$ parameters to be fitted: momentum and polar angles of each prong. The range–energy relation [6–7] and the measurement of the geometry of one event give for each assumption of charge and mass the measured values of the parameters p_i^{m}, θ_i^{m}, K_i^{m}, $i = 1 \dots N$ errors σ_{p_i}, σ_{θ_i}, σ_{K_i}. The χ^2 to be minimized is

$$\chi^2 = \sum_i \frac{(p_i - p_i^{\mathrm{m}})^2}{\sigma_{p_i}^2} + \frac{(\theta_i - \theta_i^{\mathrm{m}})^2}{\sigma_{\theta_i}^2} + \frac{(K_i - K_i^{\mathrm{m}})^2}{\sigma_{K_i}^2}$$

The four constraints are the conservation of the three components of momentum and conservation of total energy

$$\sum_i p_i \cos\theta_i \cos K_i = 0, \qquad \sum_i p_i \cos\theta_i \sin K_i = 0,$$

$$\sum_i p_i \sin\theta_i = 0, \qquad E_1 + M_t + \sum_2^N E_i = 0,$$

where

E_1 = total energy of incident particle,
M_t = target rest mass, and
E_i = total energy of prong i.

The matrixes G_x^{m}, B, G_B, R, G_x, and λ are computed as described in the previous paragraph.

At the end of the iterative fit of one hypothesis, the minimized value of the chi-square χ_0^2 gives the associated probability $P(\chi_0^2, \nu)$, ν being the number of degrees of freedom. In the ordinary case, with no neutral particles nor lost tracks, $\nu = 4$. Probabilities below a threshold value fixed according to particular experimental conditions can be rejected and the remaining hypothesis can be given a normalized probability.

4. Hypothesis with a neutral particle

A particle with zero charge is not visible in a ionographic detector. Our program examines the hypothesis including one neutron, to which is given in each iteration the momentum required to satisfy momentum conservation. The only available constraint is then conservation of energy and so, in this case, $\nu = 1$.

5. Hypothesis with a lost track

If the residual range of one prong is not known because it goes out of the detector before coming to rest, the program assigns to it the modulus of momentum that satisfies conservation of energy in each ieteration. In this case, as the three remaining constraints are those corresponding to momentum conservation, the number of degrees of freedom is $\nu = 3$.

6. Description of the program

The program is in two parts: (1) determination of geometrical parameters and (2) kinematical analysis.

The first part converts geometrical quantities directly measured on the event and their errors into residual range and polar angles $R \pm \Delta R$, $\theta \pm \Delta\theta$, $K \pm \Delta K$ and their errors for each prong.

The second part can be divided into several sections:

(a) Computation of momentum, kinetic energy and their errors for each prong by means of the measured value of residual range and its error and the range-energy relation.

(b) Generation of all compatible hypotheses of charge and mass number for each prong.

(c) Rejection of non-physical hypotheses under the requirements of momentum and energy conservation taking into account experimental errors.

(d) Determination of the values of momentum and polar angles for each prong which minimize the chi-square function and simultaneously satisfy the conservation constraints as described in sections 2 and 3.

(e) Decision on the acceptability of each fitted hypothesis and computation of the associated probability $P(\chi_0^2, \nu)$.

A flow diagram illustrating the program is given in figs, 1, 2 and 3. A block diagram of subroutines and functions is given in fig. 4. The specific role of each subroutine is explained on comment cards throughout the listing.

7. Description of data required

The input is read in the following order (see table 2)

(1) Card defining input/output units and general specifications.

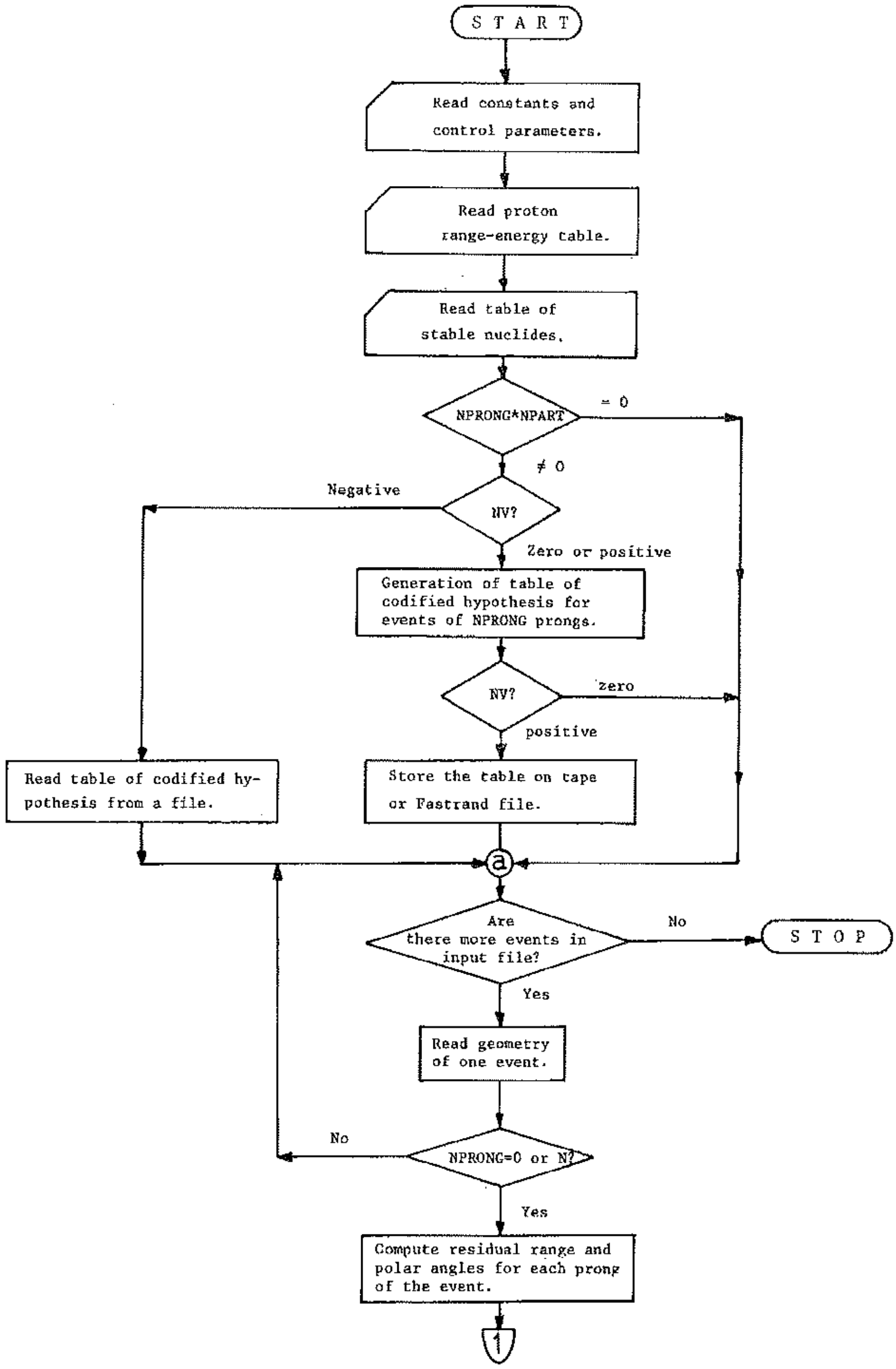
START
Read constants and control parameters.
Read proton range-energy table.
Read table of stable nuclides.
NPRONG*NPART
= 0
≠ 0
NV?
Negative
Zero or positive
Generation of table of codified hypothesis for events of NPRONG prongs.
NV?
zero
positive
Read table of codified hypothesis from a file.
Store the table on tape or Fastrand file.
a
Are there more events in input file?
No
STOP
Yes
Read geometry of one event.
No
NPRONG=0 or N?
Yes
Compute residual range and polar angles for each prong of the event.
1

Fig. 1.

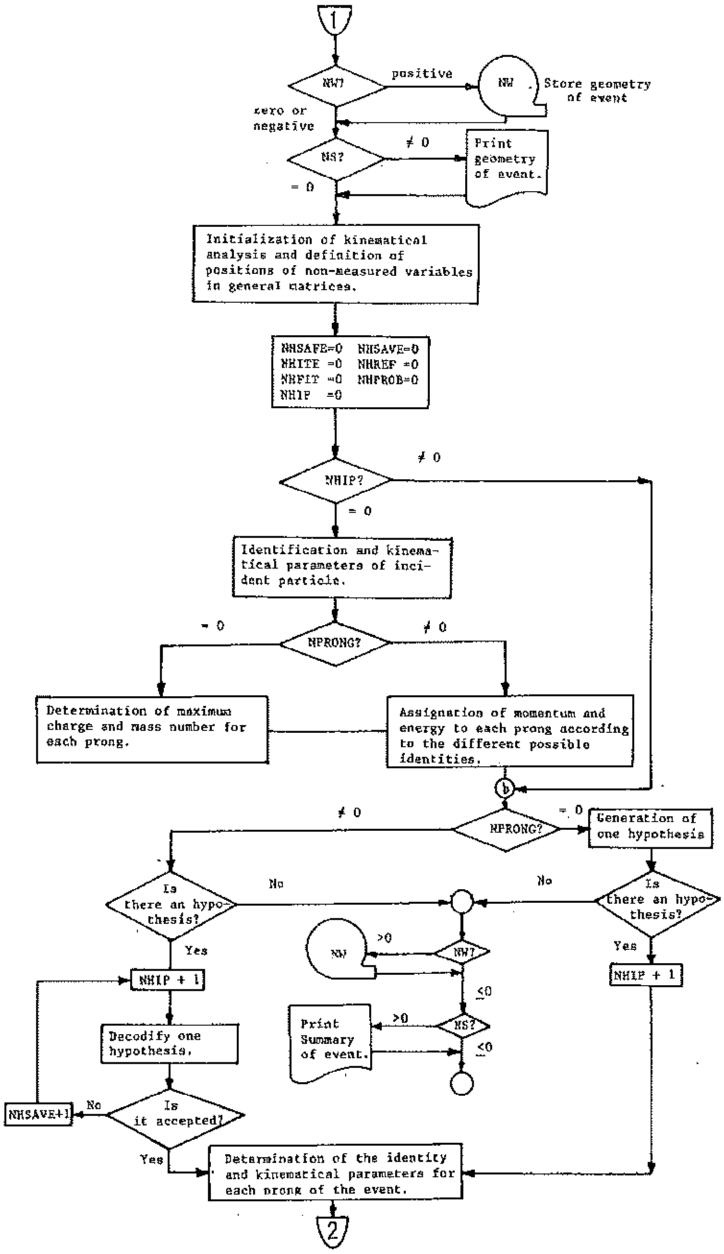

Fig. 2. Continuation of fig. 1.

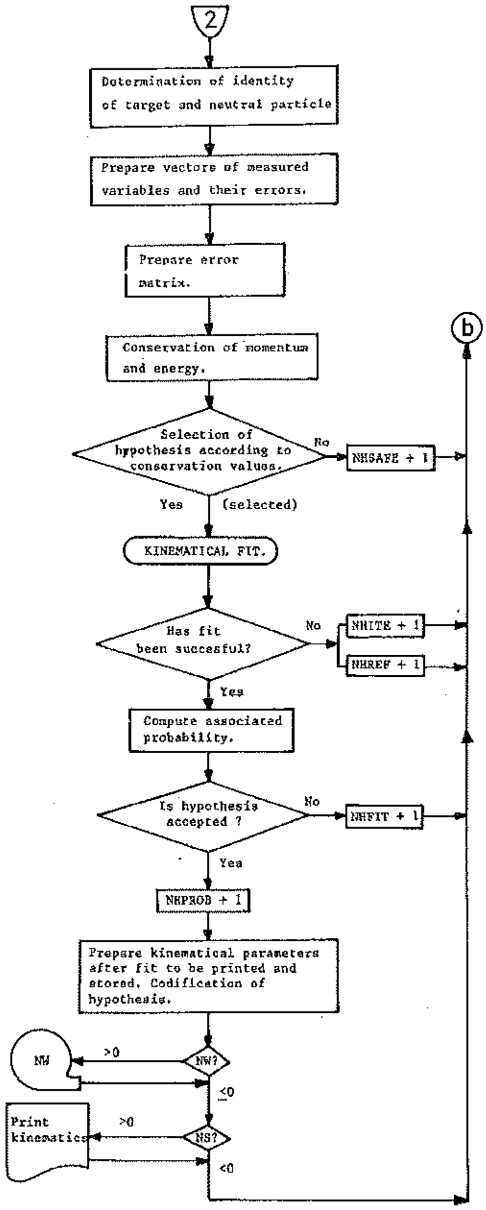

Fig. 3. Continuation of fig. 2.

Table 2

Column	Variable	Format	Description
(1)			
1–4	NLAG	I4	Interpolation degree for Lagrange method used in functions ENERG and RANGE for range–energy computations NLAG=1.
5–8	NE	I4	Card reader unit (NE=5 in UNIVAC 1108).
9–12	NS	I4	Line printer unit (NS=6 for UNIVAC 1108). If NS=0, printing is omitted. If NS=–6, a compact printed output is obtained.
13–16	NU	I4	Tape or disc file unit where measured geometric data are stored to be read by READER subroutine. If NU=5, geometry will be read from cards.
17–20	NV	I4	Input/output unit to read/write the codified hypothesis of charge and mass number for each prong compatible with charge and mass number conservation. If NV=0, the table of hypotheses is generated but not stored. If NV > 0, the table is generated and stored in file NV. If NV < 0, the table is read from catalogued file or tape file NV.
21–24	NW	I4	Tape or disc file unit where results are stored. If NW < 0, results are not stored.
25–32	NFILE	I8	Number of records already filled in file NW by a former execution and to be passed over in the present one.
33–36	NPRONG	I4	Number of prongs of events to be identified. If NPRONG=0 all events will be treated. If NPRONG=n, only n-prong events will be identified.
37–40	NPERDU	I4	Maximum number of lost tracks accepted for one event.
41–50	FSTAR	F10.1	Identification number of first event in input file to be identified. If FSTAR=0, identification is started from the first event in input file.
51–60	FEND	F10.1	Identification number of last event in input file to be identified. If FEND=0, execution stops at the end of file.
61–66	PROBLI	F6.4	Required minimum value of associated probability $P(\chi_0^2, \nu)$ for an hypothesis to be accepted.
67–72	NPART	I6	Order number of beam. If NPART < 0, the table of codified hypotheses is prepared for each event (NV is ignored).
(2)			
1–6	MITE(3)	3I2	Maximum number of allowed iterations for one hypothesis (ordinary, with neutron and with a lost track).
7–12	MCH(3)	3I2	Maximum number of allowed cut-steps for one hypothesis.
13–18	MCHITE(3)	3I2	Maximum number of allowed cut-steps for one iteration.
19–30	FACT(3)	3F4.2	Safety factor which multiplies the sum of absolute values of experimental errors. If initial conservation values are greater than this sum multiplied by FACT the hypothesis is rejected.
31–66	FEPS(3,3)	9F4.2	Final values of conservation of momentum, energy and $\partial\chi^2/\partial x$ required to stop the iteration procedure. The first index refers to ordinary, neutron and lost track cases; the second, to the values of conservation of momentum, energy and $\lvert\partial\chi^2/\partial x\rvert$
(3)			
First card:			
1–6	NREP	I6	Number of pairs (R,E) of range–energy values for proton
Following cards:			
1–72	R(I), E(I) 6F12.3 I=1, NREP		Range–energy table for proton

Table 2
Continued
(4)

First card:			
1–6	NNC	I6	Number of stable nucleides considered as possible products of the reaction
Following cards: (a card for each stable nucleide)			
1–10	ZNC	F10.3	Atomic number of stable nucleide.
11–20	ANNC	F10.3	Mass number of stable nucleide.
21–30	AMNC	F10.3	Nuclear mass in MeV.
31–40	DEFMNC	F10.3	Mass excess in MeV.
41–46	NAMENC	A6	Chemical name of element.
(5)			
Same characteristics as (4)			
(6)			
Same characteristics as (4)			
(7)			
First card: (Identification of event)			
1	N	I1	Number of prongs of event
2–13	EVENT	F12.1	Identification number of event
14–20	FAIS	F7.0	Residual range of incident particle (in microns).
21–30	DFAIS	F10.2	Error in FAIS
31–40	POT	F10.3	Average ionization potential of the detector.
41–50	APZ	F10.3	Average A/Z of the detector.
51–60	DENS	F10.3	Density of detector (in g/cm^3)
61–67	PART	F7.0	Identification number of incident beam
68–70	PROG	F3.0	Number fixing entry in READER subroutine according to input geometry.
71–72	FLINE	F2.1	Linear contraction coefficient of detector after development.
Following cards:			
1–5	LINE	I5	Order number of card in packet corresponding to one event. If negative, it represents the last of the packet for this event.
6–10	NT	I5	Order number of prong. If negative, prong has not been totally measured. If 0, card corresponds to the same prong.
11–20	L	F10.0	Projected horizontal length in ocular scale divisions.
21–30	G	F10.0	Equivalence in microns of one division of ocular scale
31–40	D	F10.0	Depth difference between corresponding points (positive for ascending tracks, negative for descending).
41–50	S	F10.0	Plate thickness when event is measured.
51–60	S	F10.0	Plate thickness before developing.
61–70	ANG, ANGM	F7.0.F3.0	Integer part of azimuthal angle referred to incident track (degrees) and fractionary part (minutes).

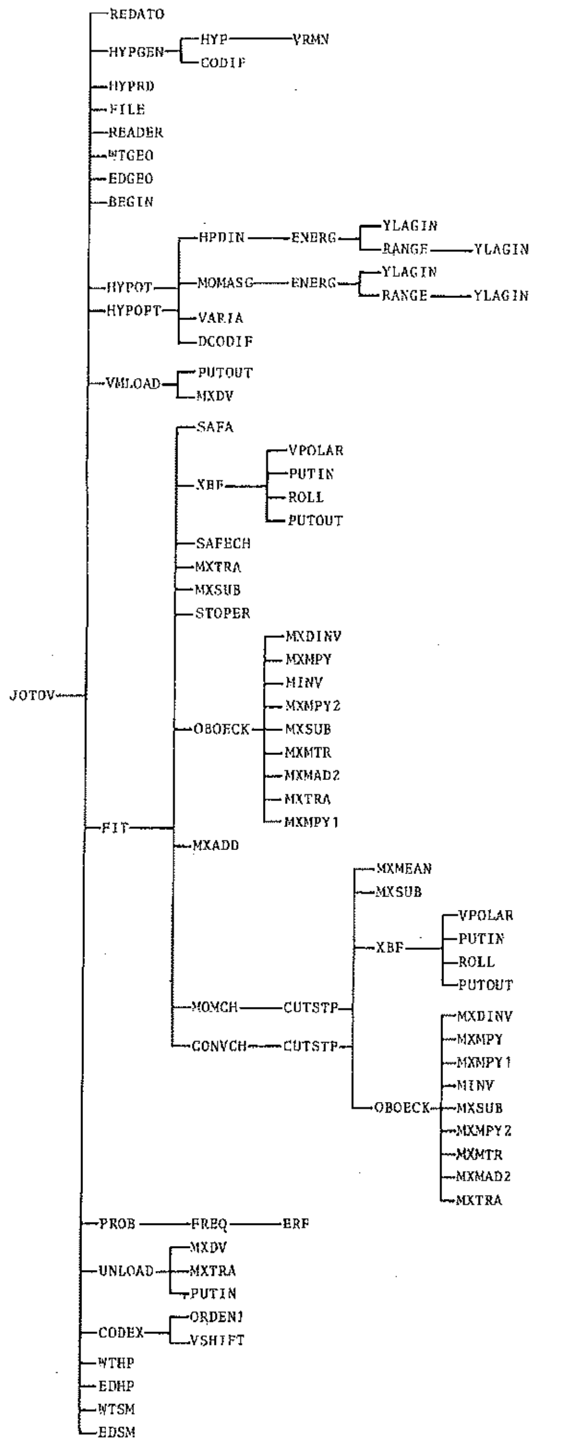

Fig. 4. Block diagram of subroutines and functions of program JOTOV.

(2) Card fixing values of control parameters governing kinematical fit.
(3) Proton range–energy table.
(4) Emergent fragments table.
(5) Possible targets table.
(6) Incident particles table.
(7) Geometry of one event (repeated as many times as there are events to identify).
(8) End of file.

8 Output description

8.1. Printed output

The test run output reproduced at the end of the paper is quite self-explanatory. This five-prong event is identified as $p+{}^{14}N \rightarrow p+t+\alpha+{}^{7}Be$ (normalized probability 95%) or $p+{}^{14}N \rightarrow p+d+t+{}^{9}Be$ (normalized probability 5%). Complete kinematics before and after fit and given. The quantities in the summary have the following meanings:

HYPOTHESIS: Number of possible hypotheses for the given event compatible with charge and mass number conservation.

SAVE: Number of hypotheses rejected before fit for having a prong with kinetic energy incompatible with incident energy.

SAFE: Number of hypotheses rejected because initial conservation values of momentum and energy are judged too unsatisfactory according to FACT.

ITE: Number of hypotheses rejected because the number of required iterations is greater than the maximum allowed.

CUTSTP: Number of hypotheses rejected because the number of cut-steps performed is greater than the maximum allowed.

FITTED and ACCEPTED: Number of fitted hypotheses with probability smaller and greater than the allowed minimum, respectively.

NFILE: Number of last filled record on tape or disc file where results are stored.

8.2. Output stored on tape or disc file

A listing of the output stored on tape on disc file is also reproduced. It is similar to the lineprinter output. Masses of particles in MeV are added to facilitate further work and labels are omitted. Geometry, kinematics and summary of one event are headed by a mark having the values 1, 2 and 3 respectively.

9. Final remarks on usage of the program

The subroutine READER which computes residual range and polar angles $R \pm \Delta R$, $\theta \pm \Delta\theta$, $K \pm \Delta K$, for each prong must be built by every user for his particular way of measuring the geometry of events. In the present version of the program, four entries are included in READER corresponding to four different systems of measurement which have been used by the authors in different experiments. (PROG = 1,2, 3,4). In the output example, the geometry was measured with a microscope equiped with goniometer, length ocular scale and a dip clock. The geometrical parameters corresponding to this system of measurement are the those indicated in the input data description.

This program has been conceived to be used with a fast and large computer of the UNIVAC 1108 or 1110 type or equivalents. In large-scale usage of the program (identification of thousands of events) the geometry of the measured events and the codified hypothesis of charge and mass number for each prong (these hypotheses are codified in octal and stored in 36 bits words to reduce occupation of central memory) should be read from catalogued files. The output should also be stored in a catalogued file. The incorporated input/output units NU, NV, NW make these operations straightforward.

References

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TEST RUN OUTPUT

```
*******   5 937645.10  55080.00    120.00   303.30     2.10       3.81       1.00       3.00       1.00                 *******

 PRONG                              R          DR          TH      DTH         K       DK
   1                        53684.131 + 130.409        .087 +   .035       .000 +  .019
   2                          265.637 +   8.314       -.323 +   .038      2.419 +  .019
   3                          304.146 +  14.385       -.006 +   .013       .333 +  .019
   4                        16655.711 + 311.540       -.208 +   .024      -.686 +  .019
   5                            6.765 +   7.984        .509 +   .513     -1.583 +  .164

 PRONG   Z    A    TARGET= 7. 14.   P          DP          TH      DTH         K       DK               CODE=       741111132447.
   1    1.   1.     MEASURED    524.473 +   8.799        .087 +   .035       .000 +  .000
                      FITTED    526.286 +   5.651        .088 +   .034       .000 +  .000
   2    1.   7.     MEASURED    234.574 +   8.072       -.323 +   .038      2.419 +  .019
                      FITTED    237.129 +   7.093       -.320 +   .040      2.420 +  .019
   3    2.   4.     MEASURED    454.530 +  17.939       -.006 +   .013       .333 +  .012
                      FITTED    446.548 +  13.053       -.007 +   .013       .338 +  .019
   4    1.   1.     MEASURED    368.479 +   7.873       -.208 +   .024      -.686 +  .019
                      FITTED    366.804 +   6.768       -.211 +   .024      -.687 +  .019
   5    4.   7.     MEASURED    251.263 +  71.101        .509 +   .513     -1.583 +  .164
                      FITTED    212.094 +  20.926       1.237 +   .062     -1.647 +  .129
  CONSERVATION OF                  PX         PY          PZ        E        CHI-SQ N PROB N WEIGHT
  ITE=  3           MEASURED    -16.517    138.702      55.141   -3.630            2.423
  CUT=  0           FITTED        -.064       .048        .074    -.001        .6584+00     .0000

 PRONG   Z    A    TARGET= 7. 14.   P          DP          TH      DTH         K       DK               CODE=       741111122349.
   1    1.   1.     MEASURED    524.473 +   8.799        .087 +   .035       .000 +  .000
                      FITTED    534.055 +   5.380        .097 +   .034       .000 +  .000
   2    1.   2.     MEASURED    177.644 +   6.088       -.323 +   .038      2.419 +  .019
                      FITTED    171.548 +   5.426       -.331 +   .044      2.411 +  .018
   3    2.   3.     MEASURED    372.849 +  14.727       -.006 +   .013       .333 +  .019
                      FITTED    394.172 +   8.789       -.006 +   .013       .329 +  .019
   4    1.   1.     MEASURED    368.479 +   7.873       -.208 +   .024      -.686 +  .019
                      FITTED    362.058 +   6.691       -.202 +   .024      -.668 +  .018
   5    4.   9.     MEASURED    276.749 +  85.506        .509 +   .513     -1.583 +  .164
                      FITTED    183.401 +  21.189       1.483 +   .129     -1.527 +  .161
  CONSERVATION OF                  PX         PY          PZ        E        CHI-SQ N PROB N WEIGHT
  ITE=  5           MEASURED     20.416    222.032      22.000   -7.277           10.437
  CUT=  0           FITTED         .189       .013        .060    -.002        .3233-01     .0000

***********************************         SUMMARY OF EVENT        937645.10          ***********************************

HYPOTHESIS    1636*     SAVE    939*     SAFE    681*     ITE      0*     CUTSTEP      0*     FITTED   14*     ACCEPT    2*
NFILE           37*
*****************************************************************************************************************************

*** CPU TOTAL TIME IS    69.1972 SEC *** LAST INTERVAL TIME IS    14.3046 SEC *** CALL NUMBER IS    3 ***

*** END-OF-FILE DETECTED ON INPUT GEOMETRY FILE ***
```

```
@DATA.L           JOVOUT.
DATA00F-RLIB67-10  02N02-23:25:24
000001  1   1
000002  0   2 5      937645.1               55080.000   120.000   303.300    2.100    3.815    1.000   3.000
000003  0   3 1                                       53684.131   130.408     .087     .035     .000    .019
000004  0   4 2                                         265.637     8.314    -.323     .038    2.419    .019
000005  0   5 3                                         304.146    14.385    -.006     .013     .333    .019
000006  0   6 4                                       16655.711   311.540    -.208     .024    -.686    .019
000007  0   7 5                                           6.765     2.984     .609     .513   -1.583    .164
000008  2   8
000009  0   9 5  741111132447.0  7.  14.  13040.010       2.423      .658     .000   3    0
000010  0  10 1                  1.   1.    938.258     524.473     8.799     .087     .035     .000    .000
000011  0  11 1                  1.   1.    938.258     526.286     5.651     .088     .036     .000    .000
000012  0  12 2                  1.   3.   2808.880     234.574     8.072    -.323     .038    2.419    .019
000013  0  13 2                  1.   3.   2808.880     237.129     7.033    -.320     .040    2.420    .019
000014  0  14 3                  2.   4.   3727.328     454.530    17.939    -.006     .013     .333    .019
000015  0  15 3                  2.   4.   3727.328     446.548    13.053    -.007     .013     .338    .019
000016  0  16 4                  1.   1.    938.258     368.479     7.873    -.208     .024    -.686    .019
000017  0  17 4                  1.   1.    938.258     366.804     6.768    -.211     .024    -.687    .019
000018  0  18 5                  4.   7.   6532.087     251.263    71.101     .609     .513   -1.583    .164
000019  0  19 5                  4.   7.   6532.087     212.094    20.926    1.237     .062   -1.647    .129
000020  0  20                                           -16.517   138.702   55.141   -3.630
000021  0  21                                             -.064      .049     .074    -.001
000022  2  22
000023  0  23 5  741111122349.0  7.  14.  13040.010      10.497      .033     .000   5    0
000024  0  24 1                  1.   1.    938.258     524.473     8.799     .087     .035     .000    .000
000025  0  25 1                  1.   1.    938.258     534.055     5.380     .097     .034     .000    .000
000026  0  26 2                  1.   2.   1875.585     177.644     6.088    -.323     .039    2.419    .019
000027  0  27 2                  1.   2.   1875.585     171.548     5.426    -.331     .044    2.411    .018
000028  0  28 3                  2.   3.   2808.350     372.849    14.727    -.006     .013     .333    .019
000029  0  29 3                  2.   3.   2808.350     394.172     8.789    -.006     .013     .329    .019
000030  0  30 4                  1.   1.    938.258     368.479     7.873    -.208     .024    -.686    .019
000031  0  31 4                  1.   1.    938.258     362.058     6.691    -.202     .024    -.668    .016
000032  0  32 5                  4.   9.   8392.629     276.749    85.506     .509     .517   -1.583    .164
000033  0  33 5                  4.   9.   8392.629     183.401    21.189    1.483     .129   -1.527    .161
000034  0  34                                            20.416   222.032   22.000   -7.277
000035  0  35                                              .189      .017     .060    -.002
000036  3  36
000037  0  37 5      937645.1                    1636       939       681        0        0       14       2

@FIN
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