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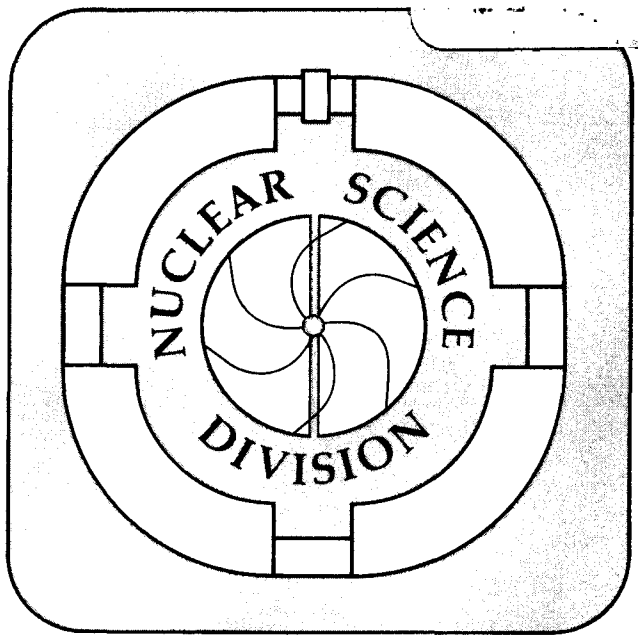

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FREESCO: Statistical Event Generator for Nuclear Collisions*

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Abstract

This paper describes the numerical code FREESCO which generates complete multi-fragment events in nucleus-nucleus collisions at beam energies from a few tens of MeV per nucleon to a few GeV per nucleon. The code represents an implementation of a statistical explosion-evaporation model describing the microcanonical disassembly of excited sources into pions, nucleons and complex nuclear fragments.

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PROGRAM SUMMARY

Title of subroutines: BOOST, DECAY, DROP, ERF0, EVAP, F, FIND, HEAT, LEVELS, LNZ, P, TEMP, TWRAN (appear in alphabetical order in the code)

Program obtainable from: CPC Program Library, Queen's University of Belfast, N. Ireland (see application form in this issue)

Computers: CDC-6600, -7600, VAX-750, -780, -8600, CRAY-1,...

Programming language used: Fortran 77

High speed storage required: 71680 bytes

Number of bits per word: 32

Peripherals required: Output device for error messages, mass storage device for nuclear data input and recording of generated events

Number of lines in program: 1779

Keywords:
nuclear collisions, statistically generated multifragment events, microcanonical description, minimal dynamics, explosion-evaporation disassembly

Nature of physical problem:
In nucleus-nucleus collisions above a few tens of MeV/N, a large number of multifragment channels are open and modern detector systems can detect nearly all the charged fragments produced. Therefore, large samples of complete events must be calculated. A well-defined, least biased reference model results from assuming that the disassembly occurs statistically.

Method of solution:
The collision produces a (small) number of sources which disassemble statistically. Highly excited sources explode quickly into a number of elementary and complex fragments; this process is simulated by random sampling of an approximate representation of the appropriate microcanonical phase space distribution. Less excited sources and metastable explosion products decay more slowly by sequential evaporation of light nuclei.

Restrictions:
The code is intended for beam energies in the range from a few tens of MeV/N to a few GeV/N.

Typical running times:
Average CPU time for 400 MeV/N ^{93}Nb + ^{93}Nb is 1.75 seconds per event on a VAX 8600.

1 Introduction

Nuclear collisions at medium and high energies have been studied extensively in the past decade and a half. The availability and improvement of sources producing strongly ionized beams of heavy ions provides the technical basis on which the field progresses. Augmented with other experimental advances and supported by strong theoretical contributions the study of energetic nuclear collisions has developed into a flurishing area with a promise to become a major interface between particle and nuclear physics that is of interest also for astrophysics.

Recent experimental developments are associated with the observation of many-fragment final states, in an effort to extract as much information as possible about the most interesting, initial stages of the reaction. Systems have been built that detect electronically practically all charged fragments emerging from the collision, and thus good-quality, nearly exclusive data on multi-fragmentation processes can be obtained [1]. Parallel to this experimental development, several ideas have been put forward that actually make use of a global event-by-event analysis to reach conclusions about the properties of hot and dense hadronic matter [2,3]. The increased interest in exclusive observables has required the calculation of complete events. In response to this need we developed a statistical model based on the available microcanonical phase space for calculating complete multifragment events in medium-energy nuclear collisions [4]. The model is applicable in an energy range from a few tens of MeV/N to energies where the creation of particles other than pions becomes important, i.e. around a few GeV/N.

The model has been implemented in the form of a Monte Carlo computer code capable of running on any standard computer. The use of the code has expanded rapidly in the past couple of years. As anticipated, it has been used both theoretically and experimentally. For example, on the theory side, it has been employed to estimate the effect of event to event fluctuations on the global observables [5], to calculate fragment yield ratios [6], and to give a quantitative measure of the collective outward motion of fragments [7]; the investigation of questions relating to entropy and the nuclear equation of state is in progress [8]. On the experimental front, the code has proven to be a useful tool, for example in the analysis of the bias introduced by the very complex detection system and in extracting the collective flow from the data [9]. It is also being used to help in the design of new equipment and experiments at the Bevalac and Brookhaven [10,11,12]. Application is just beginning at GANIL [13].

On the basis of the continually increasing interest illustrated above, we expect further potential users of our model. This situation suggests the need for a user-oriented description of the code. This is what we seek to provide in the present publication. The remainder of the write-up is organized as follows: In section 2 we introduce, and to some extent discuss, the physical problem. In section 3 the input format is specified with particular emphasis on what we call "user-supplied physical parameters". We also list the different options available for the user in the standard version of the code. The calculated results are described in section 4, and in section

5 some details are provided about specific methods. A few final remarks are made in section 6.

2 Physical Model

The collision process of two heavy nuclei is expected to be very complicated and a detailed dynamical description is beyond our present capability. However, simple geometric ideas have proven extremely useful in approximately identifying sets of nucleons that are subject to similar conditions (and behave in a distinctly different manner than other groups of nucleons) in the initial stages of the collision. Such subsystems of nucleons will be assumed independent and called *sources*. Sources with an excitation energy comparable to their total binding energy have a large number of multifragment decay channels open and will therefore disassemble in a complicated fashion. Due to its complexity the disassembly process can be described by using statistical ideas. In particular, since we address complete events and want each individual event to obey conservation laws, the microcanonical ensemble will be useful.

It is worthwile to mention at this point that (although we use concepts of equilibrium statistical physics) no equilibrium is assumed in the individual collision events. Rather, by statistically generating a large sample of collisions, we obtain a physical *ensemble*, in analogy with the experimental sampling. The physical properties of the individual systems in the ensemble of events are distributed around their most probable values, and the statistical quantities used for their characterization are the corresponding ensemble averages.

The mathematical task associated with the description of the disassembly of each individual source is to generate a sample of events distributed statistically according to the available microcanonical phase space. To accomplish this goal it is necessary to first define the phase space of the system. The selection of states that are considered to be part of the available phase space depends on physical considerations. Several choices have been made in the literature earlier [14,15,16,17,18] We believe that the present model not only concentrates on the essential physics but contains the most realistic prescription developed so far. One important ingredient is the inclusion of metastable states (stable on the time scale of the collision process) in the available phase space. As a consequence the model has to deal with the subsequent decay of the metastable states. This is the origin of the explosion-evaporation character of the model, which turns out to be quite important physically. The secondary evaporation process is described along conventional lines [19]. Note that due to the complexity of the evaporation process itself, evaporation models are also statistical in nature. The main difference between explosion and evaporation is the number and character of open decay channels. It is also convenient that sources not sufficiently excited can be treated via evaporation directly. To distinguish between explosion and evaporation we define an energy limit, the "disassembly threshold". This threshold is somewhat arbitrary, and can be modified somewhat without significant effects: in the standard version of the model described here, it has been set equal to the energy necessary for

complete disassembly into free nucleons for the particular source considered.

Once a source has been characterized by its baryon number, charge and four-momentum in a given frame of reference the code will automatically describe its two-stage (explosion-evaporation) disassembly into a number of pions, nucleons, deuterons, alpha-particles and other composite nuclei. These nuclei will either be in their ground states or in particle stable excited states that decay by gamma emission. (Electromagnetic decay is not treated in the present model.) The products of the disassembly process, i.e. the products of the collision in our statistical model, will be given in a specified Lorentz frame (usually the laboratory frame) as the result of the calculation.

We seek an approximate statistical representation of the available microcanonical phase space. This is accomplished by generating samples of multifragment events according to the ideas outlined above. Because of the care taken to use efficient methods, the code is in fact sufficiently fast to generate samples of events comparable in size to the experimental data sets.

3 Input Parameters and Options

The code requires three different types of input data: nuclear structure information characterizing the considered fragment species (including their excited levels), nuclear dynamics information determining the partition of energy and momentum among the various sources, and information specifying the particular system under study.

3.1 Nuclear Data Input

The nuclear data input of the code is provided in the form of a data file LEVEL.DAT. The contents of the standard data file is reproduced in fig. 1. This file defines the available phase space in terms of the single-fragment states that are possible ejectiles from an exploding source. In the standard version, all states in nuclei with $A \leq 16$ having a width $\Gamma \leq \Gamma_0$=1 MeV are sought to be incorporated. These states are arranged as a table of nuclear levels with associated degeneracies. To the extent possible, the table is based on available experimental information on nuclear ground-state and excited levels [20].

For heavier ($A > 4$) fragments there is insufficient experimental information at high excitation energies, so the level information has been extended upwards on the basis of an effective level density. The effective level density used consists of a Fermi-gas form (with a surface-corrected level-density parameter), multiplied by a Gaussian cut-off function expressing the probability that a state is sufficiently long lived (see ref. [4] for details). The associated width parameter ϵ_{cut} is adjusted to correspond to $\Gamma_0 = 1$ MeV. This ingredient is of course rather uncertain (but necessary), and the user may want to employ a different prescription for which excited states to include in the the available phase space. (In particular, since states stable on the time scale of the collision should be included, the life-time limit depends somewhat on the beam

```
PIons included (iff first two characters are PI) [More info at bottom.]
    0    2-1 16.15   1  0.
    1    2   13.1358 3  0.      1 -2.23
    2    2-1 15.59   1  0.
    1    3   14.9499 2  0.
    2    3   14.9313 2  0.
    1    4-1 25.92   5 -0.      3 -1.7    1 -3.2    3 -4.1
    2    4    2.4249 1  0.      1  20.3   1 -21.1   5 -22.1   3 -25.5   5 -26.4
    2    4 3-27.5    1 -29.5   3 -30.5   3 -31.0   5 -33.0
    3    4-1 25.13   5 -0.      3 -1.4    1 -3.2    3 -5.0
    1    5-1 33.798  4 -0.
    2    5   11.395  4  0.      2 -4.0    4  16.8   4 -19.9
    3    5   11.685  4  0.      2 -7.5    4  16.7   2 -18.0   6 -20.0
    2    6   17.5970 1  0.      5  1.80   5 -13.4   3  15.3
    4    7 4 -9.9    4  11.01
    5    7-1 27.941  4 -0.
    2    8   31.609  1  0.
    3    8   20.9469 5  0.      3  0.9808 7  2.26   3 -3.21   5  5.4    7 -6.1
    3    8 3  6.53   5  7.1     5 -9.0
    4    8    4.9418 1  0.      5 -2.94   1 -6.0    5 -10.0   9 -11.4  10  16.75
    4    811 18.00  24 -20.2
    5    8   22.9219 5  0.      3  0.78   7  2.32   9 -10.62
    6    8-1 35.0853 5 -0.
    3    9   24.9548 4  0.      2  2.691  4  4.31   6 -5.4    6  6.41
    4    9   11.3480 4  0.      2  1.68   6  2.43   2 -2.8    6  3.06   4 -4.70
    4    9 8 -6.8    6 -7.9    14 -11.6  21 -14.2  16 -16.2  14 -17.3
    5    9   12.4161 4  0.      2 -1.6    6  2.36   6 -2.79   4 -4.48   8 -7.0
    5    914-12.0   12 -14.6
    6    9   28.9121 4  0.      2  2.22
    3   10-1 33.833  1 -0.
    4   10   12.6076 1  0.      5  3.3680 5  5.9583 3  5.960  1  6.179  5  6.263
    4   10 7  7.37   5  7.54    9  9.27   5  9.4    14  11.0
    5   10   12.0517 7  0.      3  0.7133 1  1.7402 3  2.154  5  3.537  7  4.77
    5   10 5  5.11   5  5.16    3  5.18  28  6.3    14  7.00  10  7.67  12  8.89
    6   10   15.7029 1  0.      5  3.353  8  5.30   7  6.58
    3   11-1 40.94   4 -0.
    4   11   20.176  2  0.      2  0.3193 4  1.79   4  2.69   4  3.41  12  3.90
    4   11 4  5.25  12  5.72
    5   11    8.6679 4  0.      2  2.1247 6  4.4451 4  5.021  8  6.743  2  6.793
    5   11 5  7.286  4  7.978   2  8.56   6  8.92   8  9.19   6  9.28   4  9.87
    5   1120 10.33  16  11.49
    6   11   10.6500 4  0.      2  2.0000 6  4.319  4  4.804  2  6.339  8  6.478
    6   11 6  6.905  4  7.500   4  8.105  6  8.43   8  8.66   6  8.70   6  9.73
    6   11 8 10.08  10  10.68
    4   12   25.03   1  0.      5  2.0
    5   12   13.3695 3  0.      5  0.9531 5  1.6736 3  2.621  1  2.72   7  3.39
    5   12 5  3.76  17  4.37    3  4.99  21  5.80   8  6.8   15  7.84
    6   12    0.     1  0.      5  4.4391 1  7.65   1 -10.5   3  12.71  3  15.11
    6   1213 16.58  32  18.27
    7   12   17.3380 3  0.      5  0.96   5  1.19   4  2.00  12  3.32  15  5.32
    7   1220  9.0
```

```
 5   13   16.5624 4  0.     4  3.483  5  3.535  9  3.7    5  4.131  5  4.83
 6   13    3.1250 2  0.     2  3.0884 4  3.6844 6  3.8536
 7   13    5.3457 2  0.
 8   13   23.1051 4  0.
 5   14   23.6573 5  0.     3  0.74
 6   14    3.0199 1  0.     3  6.094  1  6.590  7  6.728  6  6.95   5  7.341
 7   14    2.8634 3  0.     1  2.3129 3  3.9478 1  4.915  5  5.1059 3  5.690
 7   14 7  5.832  3  6.204  7  6.444  5  7.028
 8   14    8.0084 1  0.
 6   15    9.8733 2  0.     6  0.740
 7   15    0.1015 2  0.     6  5.2704 2  5.2982 4  6.3239 6  7.1554 4  7.3011
 7   15 8  7.567  2  8.3128 4  8.571  14 9.2    21 9.8
 8   15    2.8555 2  0.     2  5.183  6  5.2409 4  6.176  10 6.83   8  7.276
 6   16   13.6932 1  0.
 7   16    5.6816 5  0.     1  0.1201 7  0.297  3  0.397
 8   16   -4.7370 1  0.     1  6.049  7  6.1304 5  6.919  3  7.1169
 9   16   10.629  3  0.     1  0.19   5  0.424  7  0.72   8  3.82   9  4.65
 9   1625 5.45
```

```
------------------------------------------------------------------------
                              INFORMATION
------------------------------------------------------------------------
This file contains information on the complex nuclear fragments included
in the explosion process.

PIONS: The first data card determines whether the three pions are included.
Pions are included if and only if the first two characters are PI.

NUCLEONS (neutron and proton) are always included.

COMPLEX NUCLEAR FRAGMENTS require explicit specification as follows.
For each fragment species the following data is listed:

        IZ:     CHARGE number           (first number (integer I5))
        IA:     BARYON number           (second number (integer I5))
         I:     Include species or not  (third number (integer I2))
        WW:     Ground-state MASS defect(fourth number (real F8.3))
        (If I is negative, that particular species is disregarded.)

   ... plus a pair of numbers for each intrinsic state:
        G:      DEGENERACY of the level (integer I2)
        EPS:    EXCITATION of the level (real F8.3)
        (If EPS is negative, that particular level is disregarded.)

Thus each card may contain information on a total of seven levels.
The information on the excited levels may be continued on subsequent cards,
which must then be headed by the species identification IZ (I5) and IA (I5).

NOTE:   The specific data format MUST be used (or the code modified).

For A>4, the code extends the specified level information upwards in energy
by macroscopic expressions in an attempt to include all levels with a width
less than 1 MeV. [See Fai & Randrup, Nuclear Physics A381 (1982) 557-576.]
------------------------------------------------------------------------
```

Figure 1: The data file LEVEL.DAT

An example of the contents of the data file LEVEL.DAT containing the information on the species and levels considered. The first line determines whether the three pions are included, and the remaining lines specify the complex nuclear fragments. Note that individual levels can be rendered inactive by placing a minus sign in front of the corresponding level excitation energy, and an entire species can be inactivated by having its ground-state mass defect be preceeded by a negative integer. This is often of practical convenience.

energy range addressed; the standard prescription is designed for beam energies from a few tens of MeV/N to a few GeV/N.)

In anticipation of a desire to modify the nuclear data input, a large number of low-lying levels of nuclei through $A = 16$ are included in the auxillary data file, but are conveniently suppressed (see explanation in fig. 1). Such manipulation of the nuclear level input is facilitated by an explanation at the end of the data file. (For the high intrinsic excitations, the number of levels included can be controlled by appropriate modification of the parameter C in ϵ_{cut}.[4]) The user should be aware of the fact that the running time is roughly proportional to the total number of levels included.

Finally, it should be noted that for the convenience of the user, the code has been set up so that it can actually run without the level data file, but then only with elementary fragments included (i.e. either only nucleons or nucleons and pions).

3.2 Input Format

The present version of the code it set up as an interactive program running on a VAX 8600. This has been done in order to facilitate initial or occasional use. Of course, in the typical situation, when large samples are desired, it is more practical to run the code as a remote batch job. The required modifications can easily be implemented by the individual user and their exact form depends on the specific computer system, as well as on the personal taste of the user. Most often it is preferable to precompile the bulk of the code, leaving only the input data as a variable part.

The code provides the user some flexibility with respect to the physical problem considered. First of all, the number of independently disassembling sources taken into account must be specified. This information determines the physical picture being explored. The standard version of the code contains two options for the number of sources considered (see below), but the model readily submits to the introduction of more sources (requiring correspondingly more physical input). There are several modes of the code, distinguished by the first input parameter MODE= 1, 2, 3:

Mode 1:

Disassembly of a *single* source

The requested information is as follows:

A_0, Z_0	mass and charge numbers of the source,
ϵ_0	excitation energy of the source (in MeV per nucleon),
χ	parameter governing the available volume (optional),
$\beta,\ \mu,\ \nu$	guesses for the Lagrange multipliers (optional), and
K	number of events.

Mode 2 (or 3):

Nucleus-nucleus collisions with random (or fixed) impact parameter

The requested information is as follows:

A_P, Z_P	mass and charge numbers of the projectile nucleus,
A_T, Z_T	mass and charge numbers of the target nucleus,
$EperN$	beam energy (in MeV per nucleon),
s_0	mode 2: *maximum* impact parameter (in units of $R_P + R_T$),
	mode 3: *fixed* impact parameter (in units of $R_P + R_T$),
χ	parameter governing the available volume (optional),
x_0, y_0, z_0	parameters governing the source four-momenta (optional), and
K	number of events.

3.3 User-Supplied Physical Parameters

An important user-supplied physical input parameter is the parameter χ, which controls the average available volume for the fragments arising from the exploding sources. As discussed in the Appendix of [17], this parameter is related to the break-up density ρ. If it is desired to express χ in terms of ρ, one may use the approximate relationship

$$\chi \approx \frac{\rho_0}{\rho}\frac{1}{e}(1-\frac{\rho}{\rho_0})^{(1-\rho_0/\rho)} \quad \approx \frac{\rho_0}{\rho} - \frac{1}{2} \tag{1}$$

where $\rho_0 \approx 0.17/\mathrm{fm}^3$ is the nuclear saturation density. [17] If $\chi = 0$ is entered, the value $\chi = 1$ is used, corresponding approximately to a break-up density $\rho \approx 0.7\rho_0$.

In modes 2 and 3 the code devides the collision system into three sources: the *projectile-spectator* source (denoted A), the *target-spectator* source (denoted B) and the *participant* source (denoted C). Each source is characterized by its baryon number, charge number and four-momentum. The number of nucleons in the sources is determined by the simple geometrical prescription associated with the nuclear fireball model [21,15]:

$$A = [a], \qquad B = [b] \tag{2}$$

where the real numbers a and b denote the approximate mean number of nucleons determined on the basis of the standard straight-trajectory clean-cut prescription and the brackets denote rounding down to the nearest integer. The charge numbers of the spectator sources are obtained by assuming that the charge-to-mass ratio is as in the initial nuclei. Thus

$$Z_A = [a\frac{Z_P}{A_P} + \frac{1}{2}] \tag{3}$$

$$Z_B = [b\frac{Z_T}{A_T} + \frac{1}{2}]$$

The participant baryon number and charge number are then determined by overall baryon number and charge conservation:

$$C = A_P + A_T - A - B$$
$$Z_C = Z_P + Z_T - Z_A - Z_B \tag{4}$$

We note that for asymmetric systems the smaller spectator source vanishes when the impact parameter is sufficiently small. Furthermore for a nearly head-on collision of two equal nuclei both spectator sources vanish. In addition when A or B are unity as given by the prescription (2), we take zero for their values to avoid spectator sources consisting of a single nucleon. We also demand that the participant source contain at least two nucleons, so if C (as given by (4)) is less then two, the generation procedure is aborted and restarted with a new impact parameter. The possible presence of empty sources poses no problems for the code and need not be considered separately.

The four-momenta of the sources are determined by three physical parameters x, y and z which govern the "leakage" of energy and momentum from the participant source to the spectator sources and the transverse momentum aquired by the spectator sources. (The roles of x and y are explained in ref. [4], and that of z is explained in ref. [5].) Varying in the interval [0,1], these dimensionless parameters encompass a wide range of physical scenarios and their values and/or functional dependences on energy and impact parameter are expected to be supplied by the user. The standard version of the code employs the following prescriptions:

$$x = x_0 \cdot (1 - \frac{s}{s_{max}})^2 \tag{5}$$

$$y = y_0 \cdot [1 - (\frac{s}{s_{max}})^2] \tag{6}$$

$$z = z_0 \cdot [4\frac{s}{s_{max}}(1 - \frac{s}{s_{max}})]^{1/2} \tag{7}$$

where s is the impact parameter and $s_{max} = R_P + R_T$. The parameters x_0, y_0, z_0 may be specified by the user. If entered as zero, the following default values are used:

$$x_0 = 0.2 \tag{8}$$
$$y_0 = e^{-\sqrt{EperN/(EperN)_0}}$$
$$z_0 = 0$$

with $(EperN)_0$=125 MeV.

4 Results

The program calculates K complete final events of the disassembling system. In mode 1 the code first prints one line with the following grand-canonical parameters calculated for the single source:

$$\begin{array}{c} A_0,\ Z_0,\ \epsilon_0,\ \tau,\ \beta \\ \mu,\ \nu,\ \mu_n,\ \mu_p,\ \mu_{eff} \\ \omega,\ \sigma \end{array} \tag{9}$$

Here the "effective" chemical potential is given by $\mu_{eff} = (N_0\mu_n + Z_0\mu_p)/A_0)$. Furthermore, $\omega = (\ln Z)/A_0$, where Z is the grand canonical partition function for the source, and $\sigma = \omega + \beta(\epsilon_0 - \mu_{eff})$ is its specific entropy. If the number of events K has been entered as zero, the code has completed its task and returns for new instructions.

The standard version of the code prints one line for each event generated, containing the following information:

k	event number
s_0	impact parameter
N	fragment multiplicity
ISEED1	
ISEED2	seed integers for the random-number generation
ISEED3	
dt	real time elapsed during generation of the event
t	total accumulated real time since start of first event
ΔW^2	square of the invariant-mass deficit of the event $((\mathrm{Mev}/c^2)^2)$

This is often convenient for monitoring purposes. Particularly useful is the printing of the seed integers, since this information permits exact reproduction of particular events (important for tracking down peculiarities) as well as continuation of interrupted runs. The change in the total invariant mass, ΔW, makes it possible to monitor to which extent the total four-momentum of the generated event agrees with that of the initial collision system (this numerical error is usually much smaller than one MeV/c^2). As an illustration, the complete printout from one interactive run is reproduced in fig. 2.

Since the needs vary from case to case, no other output is generated in the standard version. The extraction of further information is facilitated by a detailed comment near the end of the main program, reproduced in fig. 3. Typically, the user would want to store the following information A_P, Z_P, A_T, Z_T, $EperN$, s_0, K, χ, x_0, y_0, z_0 at the beginning of the output file, in order to provide identification of the system, user-supplied input and the number of events generated, and subsequently record the following information for each event:

$$N,\ (A_n,\ Z_n,\ W_n,\ \vec{P}_n,\ n = 1, N) \tag{10}$$

```
Csa4>run freesco
There are  50 fragment species, with a total of  592 levels.

Which mode (1 or 2 or 3) ?
2


Mode 2: Three sources, RANDOM impact parameter.

Projectile mass and charge numbers:
93,41
Projectile mass and charge numbers:          93         41
Target mass and charge numbers:
93,41
Target mass and charge numbers:          93         41
Beam energy (in MeV per nucleon):
400
Beam energy (in MeV per nucleon):  400.00000
Maximum impact parameter (units of RP+RT):
1
Maximum impact parameter (units of RP+RT):     1.00000
Parameters CHI, XX0, YY0, ZZ0:
0,0,0,0
Parameters CHI, XX0, YY0, ZZ0:   1.00000  0.20000  0.16715  0.00000
Number of events:
10
Number of events:          10

 event    s      N       ISEED1        ISEED2        ISEED3       dt      time    error
     1 0.229   122    -630874527     -64804863     224251080   7.24       7.    0.000
     2 0.516    70    1028631443   -1370671787    1145775145   3.99      11.    0.000
     3 0.803    18    1816801338     939419449   -1523906090   1.05      12.    0.000
     4 0.698    39    2136602258   -1280723799    2093792863   3.84      16.    0.000
     5 0.279   112    1090147704     284969685     335430932  18.67      35.    0.000
     6 0.438    90     760357802    -780141671     825447685  15.33      50.    0.000
     7 0.581    62    1097549269   -1765535859    1450268162   8.51      59.    0.001
     8 0.559    64    1283582899     710566329    1344403867  10.80      69.   -0.002
     9 0.932     4   -1124315271     493179797    -562249696   0.71      70.    0.000
    10 0.499    76    -303979233    -238945263    1070037409  10.95      81.    0.000



Which mode (1 or 2 or 3) ?
0
```

Figure 2: Example: 400 MeV/N ^{93}Nb + ^{93}Nb

This figure displays the printout from an interactive run with the standard code. The case considered is the reaction 400 MeV/N ^{93}Nb + ^{93}Nb. The display is fairly self-explanatory. This example is shown for illustrative purposes only; in most applications it will be preferable to submit the code as a remote batch job delivering (more complete) output to a mass storage system for subsequent further off-line analysis.

Here N is the total multiplicity (total number of fragments) of the event in question.[1] The fragments have the (arbitrary) index n and are characterized by their baryon number A_n, charge number Z_n, mass excess W_n (in units of MeV/c^2), and three-momentum $\vec{P}_n = (P_X, P_Y, P_Z)$ (in units of MeV/c in the laboratory). Note that a pion has baryon number $A = 0$, charge number $Z = -1$, 0, 1, and mass excess $W(\pi^+$ or $\pi^-)$=140 MeV/c^2 and $W(\pi^0)$=135 MeV/c^2. Furthermore, the Z-axis is chosen along the beam direction, and the X-axis is in the direction of the impact parameter (such a convention is useful for theoretical analyses of the results); the Y-axis is then in the direction of the total angular momentum.

Additional information about the fragments can be extracted from the integer variables NNF(n) and IIF(n) at the time and place where the event is recorded. The absolute value of NNF(n) indicates that fragment's position in the nuclear data table read from the file LEVEL.DAT; if NNF(n)=0, the fragment species is not contained in the table; if the fragment is produced during the evaporation stage of the disassembly, the value of NNF(n) is negative. Furthermore, the integer IIF(n) identifies the particular particle-stable excited state in which the fragment finally appears.

In addition to the standard output, the user can easily access certain other pieces of information that might be of interest. For example, one may want to know the origin of a particular fragment. This can be inferred from the value of the parameter LS=1, 2, 3 which labels the three sources A,B,C, respectively.

In order to help the user implement changes in the code, a schematic diagram of the relationship between the various routines of the code is shown in fig. 4.

5 Details about Specific Methods

The statistical generation of complete events is based on the factorization property of the exclusive probability distribution proven in [4]. The exclusive probability for obtaining a given event can be factorized into inclusive single-fragment distributions. This fact is particularly convenient when one seeks to generate a statistical representation of the exclusive multifragment distribution. To accomplish this task we proceed as follows.

To generate an event, first a random selection of one fragment is made on the basis of the corresponding inclusive one-fragment distribution. Once a fragment has been selected with its baryon number, charge number and four-momentum, the value of these conserved quantities characterizing the remaining part of the event is also known. A subsequent random selection of a second fragment can then be made on the basis of the available information. This procedure is iterated until no residual system remains.

[1]The multiplicity N may occasionally have the value zero. This indicates that the code has given up on generating that particular event, due to a too low excitation energy in one of the sources. This may frequently happen at bombarding energies below ten MeV/N, especially for large impact parameters.

```
C-----------------------------------------------------------------------C
C                                                                       C
C                              *RESULTS*                                C
C                                                                       C
C       INFORMATION ABOUT THE COMPLETE EVENT CAN NOW BE EXTRACTED       C
C                                                                       C
C-----------------------------------------------------------------------C
C                                                                       C
C       The following information is readily available:                 C
C                                                                       C
C       K        Event number    (there are KK events in the sample)    C
C       N        Fragment number (there are NN fragments in the event)  C
C                                                                       C
C       NNF(N)   Location of fragment in table of nuclear levels,       C
C                negative if fragment arises from evaporation,          C
C                zero if absent from the table                          C
C       IIF(N)   The particular (particle-stable) excited state         C
C                in which the fragment emerges,                         C
C                one for the ground state,                              C
C                                                                       C
C       IIAF(N) Mass number of fragment                                 C
C       IIZF(N) Charge number of fragment                               C
C       NUMB(N)=1000*IIAF(N)+IIZF(N)+1                                  C
C                                                                       C
C       WWF(N)   Invariant mass of fragment (in MeV/c**2)               C
C       XXF(N)   X-component of fragment momentum (in MeV/c)            C
C                (The X-axis is in the direction of the impact paramenter) C
C       YYF(N)   Y-component of fragment momentum (in MeV/c)            C
C                (The Y-axis is along the total angular momentum)       C
C       ZZF(N)   Z-component of fragment momentum (in MeV/c)            C
C                (The Z-axis is in the beam direction)                  C
C       TTF(N)   Kinetic energy of fragment (in MeV)                    C
C       EEF(N)   Total (relativistic) energy of fragment (in MeV)       C
C                                                                       C
C       The complete event can be printed out as follows:               C
C       DO 91 N=1,NN                                                    C
C   91  PRINT 119,K,N,IIAF(N),IIZF(N),WWF(N),XXF(N),YYF(N),ZZF(N)       C
C                                                                       C
C-----------------------------------------------------------------------C
```

Figure 3: Extraction of results

This figure reproduces the extended comment in the code explaining the meaning of the various calculated quantities, so that the user may easily extract the quantities of interest in the given case. They are further discussed in the main text.

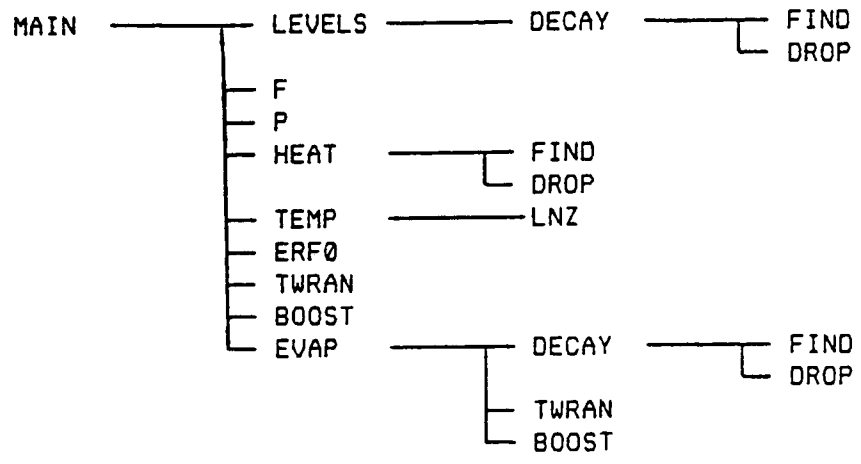

Figure 4: Schematic diagram of the code FREESCO
The figure shows the relationship between the various routines in the code. The individual routines are listed in the order of their first appearence in the routine from which they are called.

Note that the method outlined above and implemented in the code – although sequential – does not imply any "time ordering" of the emission. The order in which the fragments are generated merely represents an arbitrary enumeration of the fragments in that event and thus has only technical significance.

The inclusive single-fragment distributions appearing in the generation sequence are approximated by their truncated grand canonical equivalents. This approximation is essential in turning the procedure into a practical tool capable of generating large samples of events efficiently. The validity and detailed implementation of the method are discussed in [4]. Here we will only give a brief summary of the random selection procedure pertaining to the selection of each individual fragment as an explanation of the code.

Once a source has been characterized by its baryon number, charge and four-momentum in a given frame of reference, the code solves the constraint equations expressing conservation of total energy, baryon number and charge on the mean (in the grand canonical approximation) for the corresponding Lagrange multipliers β, μ, ν. The solution of the three coupled constraint equations for β, μ, ν is a fairly delicate numerical problem and it has proven hard to devise an efficient algoritm that will work well in all conceivable scenarios. (In particular, it should be noted that the problem is singular when the source contains only one kind of nucleon, i.e. when either $Z = 0$ (neutrons only) or $Z = A$ (protons only), in which case both μ and ν are ill-defined ($\rightarrow \infty$) and only $\mu_n = \mu + \nu/2$ or $\mu_p = \mu - \nu/2$ is well defined, respectively.) The presently implemented algoritm appears to be fairly robust, having withstood the perils of generating thousands of events in a wide variety of physical scenarios.

However, this is no guarantee that it will work universally. Experience has shown that the problems encountered most often in running the code arise from this part of the calculational task. Fortunately, it is usually easy to identify this type of problem and modify the iteration procedure so that it will work well in the given context.

Thus at each stage of the generation sequence, there is a set of a temperature parameter and two chemical potentials characterizing the appropriate source in the grand canonical approximation. Since the logarithm of the grand canonical partition function can be expressed as a computable sum over different fragment species [16], all required relative probabilities can be reconstructed with the given values of the Lagrange multipliers. For example, the inclusive probability for the creation of a fragment of a given species α is

$$P_\alpha = \omega_\alpha / \sum_{\alpha l} \omega_{\alpha l} \tag{11}$$

where ω_α is the term in the logarithm of the partition function standing for the fragment species α. On the basis of the probabilities P_α the species of a fragment is picked at random from the source. [In order to perform the random sampling, the code requires a routine producing a uniform random number between zero and one. The present code employs the VAX systems function RAN(ISEED); on different computer systems this function should be appropriately replaced.] After deciding the fragment species, the second step in the event generation is to decide on the amount of intrinsic excitation of that fragment. The relative probability of a particular excitation energy can be written down in analogy with (11) on the basis of the intrinsic partition function. The intrinsic energy is then readily decided at random according to this relative probability.

Next the fragment momentum is decided. This is done on the basis of a truncated Maxwellian distribution with a relativistic correction. The Maxwellian momentum distribution is truncated at the kinematical limit and a modified temperature τ is employed to ensure reproduction of the average kinetic energy, including relativistic contributions through second order in the small quantity τ/Mc^2. This procedure is very accurate when the produced fragment carries off only a small part of the source, and it is also accurate in the opposite limit when the source dissambles into two elementary fragments.

After selecting and fully characterizing a fragment, the characteristics of the residual source are calculated from conservation principles. If the excitation energy of the residue permits a complete disasembly into free nucleons, the code will consider it to be a modified source and start over with the procedure of picking a fragment on the basis of an updated probability of the form (11). If the residue happens to be below the disassembly threshold, its stability against light particle emission will be checked. Similarly, the stability of fragments produced in their excited states is examined.

Sources with excitation energy below the disassembly threshold, and metastable products of the explosion process, are assumed to deexcite via sequential evaporation of light nuclei. In the standard code, the following six evaporation ejectiles are considered: n, p, ^{2}H, ^{3}H, ^{3}He, ^{4}He. (The inclusion of further evaporation modes is

technically straightforward.) A simple universal treatment of the evaporation process has been designed. The decay barrier for each evaporated light particle is the sum of its separation energy and the contribution from the Coulomb repulsion between the ejectile and the daughter nucleus. This latter quantity is calculated at a suitable surface separation d which is specified for each ejectile type in an attempt to reproduce the decay information available in [20]. For these shifts we have adopted the following values (in fm): $d(n) = 0.0$, $d(p) = 1.5$, $d(^2\mathrm{H}) = d(^3\mathrm{H}) = d(^3\mathrm{He}) = 1.0$, $d(^4\mathrm{He}) = 0.5$. The values for the ejectiles with $A = 2$, 3 are somewhat arbitrary; in cases where these relatively rare evaporation modes appear to be important, the user is probably well-advised to refine the shift values.

For each excited explosion product the possibility of sequential evaporation-like decay is considered. In treating this secondary decay process, a particular evaporation channel is considered open if the excitation energy of the mother nucleus is above the corresponding barrier, calculated as described above. If no channels are open with this criterion, a second scan is performed ignoring the Coulomb barrier (so that only the ground-state Q-values are considered); the thus selected channels correspond to tunneling processes and are therefore expected to be substantially slower.

If one or more evaporation channels are open, the actual evaporation channel, as well as the excitation energy of the daughter nucleus, are selected by random competition among the open channels, taking account of their different statistical weight. Finally, the ejection direction is picked uniformly over 4π. (See Section 4 of [4] for details.)

6 Remarks

Interactions between the fragments are neglected in the model. While this approximation is expected to be less serious for dilute (χ large) or hot (τ large) systems, it may distort the fragment distribution significantly for relatively dense and cold sytems in which the long-range Coulomb repulsion tends to favor disassembly into a few large fragments [22].

Because of the increasingly wide usage of the code, it is useful to have a name associated with it. For this purpose we have devised the acronym FREESCO. The name is composed to remind of the fact that the code simulates nuclear fragmentation based on the Explosion-Evaporation model [17]: FRagmentation-by-Explosion/Evaporation Simulation Code. Of course, the phonetic similarity with a colloquial term for the major city in the area where the code was developed is not accidental and might be of help for memorizing the name. (In fact, the use of city names for statistical fragmentation codes has a long tradition.)

Finally, it should be emphasized that the model, and its present numerical implementation, are intended to provide a simple, well-defined reference against which to judge both more refined and specific models and the experimental data; in addition it may be valuable as a simulator of actual experiments involving complex detection systems whose responses are not easily understood.

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