

## APPENDIX III

This Appendix contains the detailed description of models and codes as revealed by the answers to the questionnaire in which this information was requested in the specifications of the exercise.

### Index

1	MECC7 + EVAP_F Questionnaire
2	HETC/KFA2 Questionnaire
3	HETC-3STEP Questionnaire
4	HETC/BRUYERE Questionnaire
5	CEM95 Questionnaire
6	HETC-FRG Questionnaire
7	INUCL Questionnaire
8	ISABEL-EVA Questionnaire
9	ISABEL/SMM Questionnaire
10	PACE + MSM Questionnaire
11	MSDM Questionnaire
12	CASCADE Questionnaire
13	DISCA Questionnaire
14	ALICE 92 Questionnaire
15	ALICE-IPPE Questionnaire
16	AREL Questionnaire
17	HMS-ALICE Questionnaire
18	PEQAG2 Questionnaire
19	FKK-GNASH Questionnaire
20	MINGUS Questionnaire
21	QMDRELP + SDMRELP Questionnaire
22	SPALL (modified)/YIELD Questionnaire

1

## MECC7 + EVAP\_F

### Code Information Questionnaire

#### I. General Questions:

1. Name of the code

MECC7 + EVAP\_F

2. Name of the participant

G. Youinou, F. Atchison, H.U. Wenger

3. Responsible author of the code

H. W. Bertini (ORNL) for MECC7

L. W. Dresner (ORNL) for EVAP

F. Atchison (PSI) fission modified version of EVAP plus translation of MECC7 to VAX

4. Reference of the code

MECC, H. W. Bertini Phys. Rev. 188 (1969) 1711

EVAP, L. W. Dresner ORNL-TM-196 (1962)

Fission, F. Atchison paper II, Juel. Conf. 34, 17 (1980)

5. Is a manual available?

A manual for the VAX version of HET (of which MECC etc., are parts) is available.

6. What nuclear reaction models are contained?

Medium energy intra-nuclear cascade

Evaporation

Fission

7. Range of targets allowed

$5 < A < 260$

8. Range of projectiles allowed

Nucleons and charged pions

9. Incident energy regime permitted

Nucleons  $15 < E < 3500$  MeV

Pions  $2.5 < E < 2500$  MeV

#### II. Specific Questions:

1. How are reaction cross-sections generated in the entrance channel?

Entrance channel reaction cross-sections calculated (Serber model).

2. What nuclear density distribution is used, and how does it enter the calculation?

3-region nucleus with densities based on measurements of Hoffstadter (Rev. Mod. Phys. 28, 214 (1956)). No refraction.

**3. Is the Fermi energy calculated in a local density approximation?**

Yes.

**4. What nuclear radius parameterization is used?**

Fixed data for nucleus "target-area" (outer radius of region 3).

**5. For INC models**

See Bertini report (Phys. Rev. 188 (1969) 1711. No modification of the physics content has been made in producing the VAX version but the mass-range allowed has been extended to 260.

**6. If there is a precompound phase, describe the PE model used, parameters, i.e., partial state densities, transition rates?**

No pre-equilibrium phase in the calculation.

**Are clusters multiple PE decay, relativistic kinematics used?**

**How are angular distributions computed?**

**Source of inverse cross-sections?**

**7. What physics are used for the final de-excitation state: evaporation model, Fermi breakup?**

Evaporation model as described by Dresner ORNL-TM-196 (1962) with following changes (i) velocity dependent term to coulomb barrier, (ii) fission competes with neutron emission for  $Z > 70$ , (iii) Q-values based on the 1983 mass table (A. H. Wapstra and G. Audi Nucl. Phys. A432, (1985) 1).

**Describe parameters used: level densities, inverse cross-sections or transmission coefficient, choice of optical model parameters if relevant (or reference to source), range of excitations allowed, inclusive or exclusive results?**

**8. Is there any limit as to the number of nucleons from target for which yields may be calculated?**

In principle no, but:

- (i) Binding energies for each element extrapolated (where necessary) to cover range +/- 15 masses from "most-stable" smoothly and used as "fixed" data. Nuclei outside this range during the evaporation process use values from the Cameron mass formula. No smooth joining of these regions attempted which leads to obviously silly end-state nuclei occasionally!
- (ii) Evaporation of n, p, d, t, 3-He and 4-He only treated (evaporation terminated if nucleus corresponds to a cluster).
- (iii) Be-8 breakup automatic.

**9. Any other comments on aspects not considered in the above questions?**

The MECC and EVAP\_F codes are the "heart" of HETC and the benchmark calculations have been performed using a program that links to the same OBJECT modules as used by our VAX version of HETC.

**10. References to the literature or reports discussing these codes as implemented?**

**Code Information Questionnaire****I. General Questions:****1. Name of the code**

HETC/KFA2

**2. Name of the participant**

R. Michel, M. Gloris

**3. Responsible author of the code**

P. Cloth

**4. Reference of the code**

See References 1-6

**5. Is a manual available?**

Yes

**6. What nuclear reaction models are contained?**

Bertini INC used in these calculations. Evaporation model of Weisskopf-Ewing<sup>7</sup>, with fission model of Fong (level density parameters by Baba for evaporation stage<sup>8</sup>)

**7. Range of targets allowed**

Unrestricted

**8, 9 Projectiles and energy regime**

Nucleons to 3.5 GeV (scaling law above)  
Pions to 2.5 GeV (scaling law above)

**II. Specific Questions:**

The INC used is the unmodified Bertini model as implemented in the HETC code. The fission model is the statistical model of P. Fong. The nuclei at the end of the INC stage are put into the evaporation routine.

**1. How are reaction cross-sections generated in the entrance channel?**

Three density zone geometric picture of Bertini<sup>2</sup>.

**2. What nuclear density distribution is used, and how does it enter the calculation?**

See (1)

**3. Is the Fermi energy calculated in a local density approximation?**

Yes

**4. What nuclear radius parameterization is used?**

5. **For INC models**
6. **If there is a precompound phase, describe the PE model used, parameters, i.e., partial state densities, transition rates?**

No PE phase.

**Are clusters multiple PE decay, relativistic kinematics used?**

**How are angular distributions computed?**

**Source of inverse cross-sections?**

7. **What physics are used for the final de-excitation state: evaporation model?**

**Describe parameters used: level densities, inverse cross-sections or transmission coefficient, choice of optical model parameters if relevant (or reference to source), range of excitations allowed, inclusive or exclusive results?**

Level density parameters due to Bab<sup>a</sup>.

8. **Is there any limit as to the number of nucleons from target for which yields may be calculated?**

No

9. **Any other comments on aspects not conserved in the above questions?**

10. **References to the literature or reports discussing these codes as implemented?**

1. Radiation Shielding Information Center, "HETC Monte Carlo High-Energy Nucleon-Meson Transport Code", Report CCC-178, Oak Ridge National Laboratory (August 1977).
2. H. W. Bertini, Phys. Rev. 188 (1969) 1711.
3. P. Cloth, D. Filges, G. Sterzenbach, T. W. Armstrong, and B. L. Colborn, Kernforschungsanlage Jülich Report Jül-Spez-196, 1983.
4. T. W. Armstrong, P. Cloth, B. L. Colborn, D. Filges, and G. Sterzenbach, in Proceedings of ICANS VII, AECL Report AECL-8488, 1984, p. 205.
5. T. W. Armstrong, P. Cloth, D. Filges, and R. D. Neff, Kernforschungsanlage Jülich Report Jül-1859, 1983.
6. T. W. Armstrong, P. Cloth, D. Filges, and R. D. Neef, Nucl. Instrum. Methods. Phys. Res. A 222, 540 (1984).
7. V. F. Weisskopf, Phys. Rev. 52, 295 (1937); V. F. Weisskopf and H. D. Ewing, *ibid.* 50, 475 (1940).
8. H. Baba, Nucl. Phys. A159, 625 (1970).

#### **MONTE CARLO SIMULATIONS: HETC/KFA-2**

The present calculations are based on the intranuclear cascade-evaporation model originally developed by Bertini [1], and implemented in the high-energy nucleon-meson transport code [2] developed at Oak Ridge National Laboratory (ORNL). This Monte Carlo code for particle production and radiation transport has been modified several times in the past. Various code modifications of HETC have been made at the Forschungszentrum Jülich (KFA). All the modifications relevant to the included nuclear model refer to the evaporation model, which involves the Ewing-Weisskopf formalism [3] without a contribution from preequilibrium processes. The changes contain an update of the atomic masses using the 1977 Atomic Mass Evaluation values of Wapstra and Bos [4]. The range of possible residual nuclei was extended by implementing the semi-empirical mass formula of Cameron [5] in case of masses not covered by those tables. Furthermore, the parameter  $B_0$  in the formula of the level density is allowed to vary with  $A$ , using data compiled by Baba [6]. A new kinematic calculation involving the recoil momentum of the residual nucleus allows non isotropic evaporation. At last the high energy fission model (RAL-model [7]) has been included in the evaporation model based on the statistical model of Fong [8]. In the actual update this modified HETC has been implemented

into the framework of the HERMES code system [9], resulting in the actual version HETC/KFA-2.

The calculational predictions of proton induced neutron emission presented were made by using the so-called "thin target"-setup of HETC/KFA-2. In this setup only the included nuclear models of HETC are taken into account. Starting an on-line analysis of emitted nucleons directly after their emission from the nucleus, time consuming extranuclear transport algorithm are switched off. This procedure is somewhat different from previous published calculations [10] avoiding the writing of large event histories on computer storage devices. Physically this setup can be understood as an ideal thin target consisting of only one nucleus. This method is valid because the 'geometrical' cross section of the bombarded nucleus is known by the code [9]. This method results in significantly shorter computing times than another method simulating the geometry of a real thin target used in experiments. For U and Pb targets the RAL fission model [7] with a constant value of  $B_0 = 8$  MeV and isotropic emission of secondary particles during evaporation in the laboratory system were used. For all other target nuclei the fission model was excluded and the variable  $B_0$ -option was selected, while non-isotropic emission of evaporation particles was allowed.

To achieve optimum comparison, identical energy intervals as used in the experimental analysis were provided in the HETC calculations. Depending on target material, emission angle and incident proton energy, the number of spallation events varied from  $2.5 \cdot 10^5$  to  $6.0 \cdot 10^5$  to achieve reasonable statistics in the calculations.

- [1] H. W. Bertini, Phys. Rev. 188 (1969) 1711.
- [2] T. W. Armstrong, K. C. Chandler, Nucl. Sci. Eng. 49 (1972) 110.
- [3] V. F. Weisskopf, Phys. Rev. 52 (1937) 295; V. F. Weisskopf and D. H. Ewing, *ibid* 50 (1940) 475.
- [4] A. H. Wapstra, K. Bos, At. Data Nucl. Data Tables 9 (1977) 175.
- [5] A. G. Cameron, Can. J. Phys. 35 (1957) 1021; 36 (1958) 175.
- [6] H. Baba, Nucl. Phys. A159 (1970) 625.
- [7] F. Atchison, Meeting on Targets for Neutron Beam Spallation Sources, KFA Jülich, Report Jül-Conf-34, 17 (1980).
- [8] P. Fong, Statistical Theory of Nuclear Fission, Gordon and Breach Science Publishers, New York (1969).
- [9] P. Cloth, D. Filges, R. D. Neef, G. Sterzenbach, Ch. Reul, T. W. Armstrong, B. L. Colborn, B. Anders, H. Brückmann, KFA-Report Jül-2203 (1988).
- [10] D. Filges et al., Physical Review C36 (1987) 1988.

### 3

## HETC-3STEP

### Code Information Questionnaire

#### I. General Questions:

##### 1. Name of the code

HETC-3STEP

##### 2. Name of the participant

H. Takada, N. Yoshizawa, K. Ishibashi and Y. Nakahara

##### 3. Responsible author of the code

N. Yoshizawa

##### 4. Reference of the code

N. Yoshizawa, K. Ishibashi and H. Takada, Development of High Energy Transport Code HETC-3STEP Applicable to Nuclear Reaction with Incident Energies above 20 MeV, J. Nucl. Sci. Technol. 32, No. 7,601 (1995).

##### 5. Is a manual available?

No, but being prepared at present

Input data and output list are almost the same as those of HETC-KFA2. New input data for the preequilibrium calculation was added.

##### 6. What nuclear reaction models are contained?

- (1) Intranuclear cascade model developed by H. Bertini [1].
- (2) Precompound decay with closed form exciton model.
- (3) Evaporation model based on Weisskopf-Ewing model.
- (4) Fission model developed by F. Atchison [2]. The model is based on the statistical model using empirical formulas as far as possible.

These models are the same as the ones implemented in HET-KFA2 [3] except for the precompound decay calculation.

##### 7. Range of targets allowed

$A = 1, 8 \leq A \leq 239$

##### 8. Range of projectiles allowed

$p, n, \pi^+, \pi^-, \pi^0, \mu^+, \mu^-$

##### 9. Incident energy regime permitted

1 TeV

#### II. Specific Questions:

##### 1. How are reaction cross-sections generated in the entrance channel?

As the total cross sections, geometrical cross sections,  $\sigma_g$ , are used, which are calculated from the nuclear radius data stored in the nuclear structure data base 'CRSC' in the code. The reaction cross section,  $\sigma_r$ , is obtained by the Monte Carlo calculation as



$$r_g = N_r / N_t,$$

where  $N_t$  is the number of total events and  $N_r$  is the number of non-elastic events.

## 2. What nuclear density distribution is used, and how does it enter the calculation?

A nucleus is divided into three regions. For each region  $i$ , the density parameter  $\rho_i$  is given also in the data base CRSC:

The neutron density  $n_i^n$  in the region  $i$  is given by

$$n_i^n = \rho_i \cdot (A - Z).$$

The proton density  $n_i^p$  is given by

$$n_i^p = \rho_i \cdot Z$$

where  $A$  and  $Z$  are the mass and atomic numbers, respectively.

## 3. Is the Fermi energy calculated in a local density approximation?

The Fermi energy is also parameterized as follows, using the parameters  $U_i$  stored in the data base CSRC, i.e.,

$$\text{for neutrons, } E_i^n = U_i (A - Z)^{2/3},$$

$$\text{for protons, } E_i^p = U_i Z^{2/3}.$$

## 4. What nuclear radius parameterization is used?

The outer radius (nuclear radius) and two concentric radii to define the inner regions.

## 5. For INC models

### a. What nucleon-nucleon cross sections are used? Are they energy and isospin dependent?

The free nucleon-nucleon cross sections compiled by H. W. Bertini in 1963 [1] are used even now. The cross sections are given for nucleons in the energy region below 3.5 GeV, while they are given for charged pions up to 2.5 GeV. For nucleon-nucleon and pion-nucleon non-elastic collisions at higher energies, the information at 3.5 GeV (if the particle is a proton or neutron) or at 2.5 GeV (if the particle is a charged pion) are used as the input to scaling routines that use the extrapolation method of Gabriel, Alsmiller, Jr., and Guthrie.

It is reported that HETC has been run successfully for energies up to 1 TeV but the comparison of HETC results with experimental data have been made only for energies  $\leq$  30 GeV.

### b. How is Pauli exclusion handled in the INC?

The Pauli exclusion principle at INC process is treated as follows: the nucleons of the target are assumed to occupy all the energy levels up to the Fermi energy. When a nucleon-nucleon collision is simulated, the energies of the two nucleons after the collision are compared with the Fermi energy. If both energies are greater than the Fermi energy, the collision is allowed and the directions of motion of the nucleons are determined based on the differential cross sections. If the energy of one of the nucleons is lower than Fermi energy, the collision is prohibited and a new collision point is sampled and new collision simulation is performed. This procedure is applied until the energies of all the moving particles become lower than the cascade cut-off energy or the

nucleons go out of the nucleus. Here, the cascade cut-off energy is set equal to the Fermi energy for neutron, while to the Fermi energy plus Coulomb barrier for proton.

**c. How are the nuclear density effects treated?**

The nuclear density effects are considered only as the nucleon density distribution at the beginning of the calculation described in 2.

**d. How are ejectil binding energies handled?**

The value 7 MeV is used for all nuclides and everywhere inside the nucleus.

**e. Is any nucleon-cluster scattering considered?**

A correlated two nucleon cluster is not taken into consideration in code.

**f. Are ejectiles subject to surface refraction/reflection angular distribution?**

No, the surface refraction/reflection are not considered in the code.

**g. What channels other than neutron and proton are treated e.g. alpha, deuterons, tritons, pi, K, p etc.?**

$\pi^+$ ,  $\pi^-$ ,  $\pi^0$ ,  $\mu^+$ ,  $\mu^-$ .

**h. How is the transition made to the next phase of the calculation?**

The next phase is precompound. The cascade process is terminated by the use of a probability function  $f(E_c)$  for suppressing low-energy particle emission. This method is adapted to exclude the precompound effect in the cascade calculation. The form of  $f(E_c)$  is given by

$$f(E_c) = \left(1 - \frac{E_c}{E_0}\right)$$

where  $E_0$  is adjusted to 40 MeV.

**6. If there is a precompound phase, describe the PE model used, parameters, i.e., partial state densities, transition rates?**

**Are clusters, multiple PE decay, relativistic kinematics used?**

**How are angular distributions computed?**

**Source of inverse cross-sections?**

Monte Carlo algorithms formulated by Y. Nakahara and T. Nishida [4] by the use of the exciton models proposed by J. J. Griffin, C. Kalbach and K. K. Gudima, et al.. The procedure of the precompound decay simulation in HETC-3STEP is described in Ref. 5.

- Nuclear angular momenta and shell structures are not taken into consideration.
- The exciton state density  $w(p, h, E)$  proposed by Kalbach, using the Griffin's model.
- Spin dependent particle emission rate.
- Cluster emissions can be treated.
- The transition rate on interaction between excitons formulated by Gudima et al., was modified and increased up to a factor of F:

$$F = \max\left(0.2, 3.4 - \frac{13}{\sqrt{A}}\right),$$

where  $A$  is the mass number of a target nucleus. The resultant transition rate  $\Lambda$  in the preequilibrium process is expressed as:

$$\Lambda = F \cdot (\lambda_+ + \lambda_0 + \lambda_-) + \sum_{j=1}^6 \Gamma_j,$$

where

$\lambda_+$  : transition probability for increasing the number of excitons,

$\lambda_0$  : transition probability for not changing the number of excitons,

$\lambda_-$  : transition probability for decreasing the number of excitons,

$\Gamma_j$  : emission rate of particle  $j$ ,

$j$  : neutron ( $j=1$ ), proton ( $j=2$ ), deuteron ( $j=3$ ), triton ( $j=4$ ),  $^3\text{He}$  ( $j=5$ ) and  $^4\text{He}$  ( $j=6$ ).

- Relativistic kinematics are not used.
- Angular distribution: basically isotropic as the multistep compound process.
- The number of particles in the exciton state,  $p_0$ , is taken to be equal to the number of particles whose histories have been terminated during INC, because of the energy decrease below one-half of the Coulomb barrier. The number of holes,  $h_0$ , is taken to be  $h_0 = p_0 - 1$ .

#### 7. What physics are used for the final de-excitation state: evaporation model, Fermi breakup?

For final de-excitation calculation of a residual nucleus, the EVAP program [6] is used. This program was written originally by L. Dresner and was revised later by M. Guthrie. In HETC-3STEP, the fission process was treated as a competitive process with the evaporation process by the use of the high energy fission model developed by F. Atchison [2].

**Describe parameters used: level densities, inverse cross-sections or transmission coefficient, choice of optical model parameters if relevant (or reference to source), range of excitations allowed, inclusive or exclusive results?**

The level densities compilation by H. Baba [7] has been used in the code. The mass formula derived by A.G. Cameron [8] and the atomic mass table evaluated by A.H. Wapstra [9] have also been employed so far. In this activation yield benchmark, however, those parameters were derived as follows: the level densities derived by Ignatyuk [10] with parameters proposed by Mengoni et al. [11] were used. The mass formula derived by Tachibana et al. [12] and the atomic mass table evaluated by Audi and Wapstra [13] were employed. As for the inverse cross sections, the values were obtained by the empirical formula derived by Dostrovsky [14].

#### 8. Is there any limit as to the number of nucleons from target for which yields may be calculated?

No, there is not any artificial limit as to the number of nucleons.

#### 9. Any other comments on aspects not considered in the above questions?

Fission process: F. Atchison's model [2]

#### 10. References to the literature or reports discussing these codes as implemented?

[1] H.W. Bertini, Phys. Rev. **188** (1969) 1711.

[2] F. Atchison, Spallation and Fission in Heavy Metal Nuclei under Medium Energy Proton Bombardment, Proc. of Meeting on Targets for Neutron Beam Spallation Source, KFA-Jülich, Germany, June 11-12, 1979, *Jül-Conf 34* (1980)

- [3] Y. Nakahara and T. Nishida: Monte Carlo Algorithms for Simulating Particle Emissions from Pre-equilibrium States during Nuclear Spallation Reactions, JAERI-M86-074 (1986).
- [4] P. Cloth et al., "HERMES (High Energy Radiation Monte Carlo Elaborate System)", KFA-IRE-E AN/12/88, 1988.
- [5] N. Yoshizawa, K. Ishibashi and H. Takada, Development of High Energy Transport Code HETC-3STEP Applicable to Nuclear Reaction with Incident Energies above 20 MeV, J. Nucl. Sci. Technol.**32**, No. 7 (1995) 601.
- [6] L.W. Dresner, EVAP - A Fortran Program for Calculating the Evaporation of Various Particles from Excited Compound Nuclei, ORNL-TM-196 (1962).
- [7] H. Baba, Phys. Rev.**A159**(1970) 625.
- [8] A.G.W. Cameron et al., Can. J. Phys**35** (1957) 1021.
- [9] A.H. Wapstra et al., Atomic Data and Nuclear Data Tables**19** (1977) 175.
- [10] A.V. Ignatyuk, Phys. Rev.**C47** (1993) 1504.
- [11] A. Mengoni et al., J. Nucl. Sci. Techn**31** (1994) 151.
- [12] T. Tachibana et al., Atomic Data and Nuclear Data Tables**39** (1988) 251.
- [13] G. Audi et al., Nucl. Phys.**A565** (1993) 1.
- [14] I. Dostrovsky et al., Phys. Rev**116** (1959) 683.

## 4

## HETC/BRUYERE

### Code Information Questionnaire

#### I. General Questions:

1. Name of the code

HETC/Bruyere

2. Name of the participant

Jean Luc Flament

3. Responsible author of the code

K.C. Chandler and T.W. Armstrong, modified by Olivier Bersillon

4. Reference of the code

ORNL 4744 (1972)

5. Is a manual available?

no

6. What nuclear reaction models are contained?

- intranuclear cascade	Bertini
- precompound decay	no
- evaporation	Weisskopf-Ewing
- fission model	Atchison

7. Range of targets allowed

no limitations

8. Range of projectiles allowed

p, n, p, m, d, t,  $^3\text{He}$ ,  $^4\text{He}$

9. Incident energy regime permitted

50 MeV - 2.5 GeV

#### II. Specific Questions:

1. - 5. no modifications from the original version

1. How are reaction cross-sections generated in the entrance channel?

2. What nuclear density distribution is used, and how does it enter the calculation?

3. Is the Fermi energy calculated in a local density approximation?

4. What nuclear radius parameterization is used?

5. For INC models
6. If there is a precompound phase, describe the PE model used, parameters, i.e., partial state densities, transition rates?

no

**Are clusters multiple PE decay, relativistic kinematics used?  
How are angular distributions computed?  
Source of inverse cross-sections?**

7. What physics are used for the final de-excitation state: evaporation model?

level densities:	Ignatyuk formula
inverse cross sections:	geometric
range of excitations allowed:	no limitation

**Describe parameters used: level densities, inverse cross-sections or transmission coefficient, choice of optical model parameters if relevant (or reference to source), range of excitations allowed, inclusive or exclusive results?**

8. Is there any limit as to the number of nucleons from target for which yields may be calculated?

no

9. Any other comments on aspects not covered in the above questions?

10. References to the literature or reports discussing these codes as implemented?

**Code Information Questionnaire****I. General Questions:****1. Name of the code**

CEM95

**2. Name of the participant**

Stepan G. Mashnik

**3. Responsible author of the code**

The authors of the primary version of the code named MARIAG are K.K. Gudima, S.G. Mashnik and V.D. Toneev. The author of the present modified version of the code named CEM95 is S.G. Mashnik.

**4. Reference of the code**

The code CEM95 is an extended version of the previous version named CEM92M. CEM95 differs from CEM92M in the following: input and output files were modified; useful comments have been added; minor observed errors are corrected. The code CEM95 allows us to calculate reaction, elastic, fission and total cross-sections; nuclear fissilities; excitation functions; nuclide distributions; energy and angular spectra; double-differential cross-sections; mean multiplicities, i.e., the number of ejectiles per incident bombarding particle; ejectile yields; mean energies and production cross-sections for n, p, d, t, He3, He4, pi-, pi0 and pi+ emitted in nucleon- and pion-induced reactions using the Cascade-Exciton Model (CEM) of nuclear reactions [1]. A detailed description of the standard version of CEM may be found in Ref. [1]. Further extensions of the CEM incorporated in the code CEM95 are described in Refs. [2-4]. Part of the primary version of the code concerning the pre-equilibrium and equilibrium stages of the reactions may be found in Ref. [5]. The Dubna version of the intranuclear cascade model used in the CEM95 is described in detail in the monograph [6].

Primary version of the majority subroutines used in CEM95 to describe the cascade stage of reactions is published in Ref. [7]. A detailed description of subroutines used at the cascade stage of the reaction in CEM95 is given in Ref. [8].

**5. Is a manual available?**

Yes. A new manual with a detailed description of all subroutines of the recent modified version of the code is in preparation.

**6. What nuclear reaction models are contained?**

The code CEM95 is intended for the Monte Carlo calculation of nuclear reactions in the framework of the CEM [1]. The CEM assumes that reactions occur in three stages. The first stage is the intranuclear cascade. The excited residual nucleus formed after the emission of cascade particles determines the particle-hole configuration that is a starting point for the second pre-equilibrium stage of the reaction. The subsequent relaxation of the nuclear excitation is treated in terms of the exciton model of preequilibrium decay which includes the description of the equilibrium evaporative stage of the reaction.

In the CEM angular distributions for particles emitted at the preequilibrium stage of the reaction may be calculated from N-N scattering, or (by analogy of the Moving Source Model) under the assumption that the momentum of a residual nucleus formed after the cascade stage of the reaction should be attributed only to n excitons rather than to all A nucleons. Then particle

emission will be isotropic in the proper n-exciton systems, but some anisotropy will arise in both the laboratory and center-of-mass reference frame. Both methods give rise to similar distributions for preequilibrium particles. In CEM95, I used the first method to allow for the asymmetry of particles emitted at the pre-equilibrium stage.

In the CEM95, evaporation is calculated by the Monte Carlo method in the statistical theory of Weisskopf-Ewing.

In comparison with the primary version of the code, CEM95 includes shell and pairing corrections, competition between particle emission and fission at the compound stage of reactions; uses more realistic nuclear level density (with N, Z, and E dependencies of the level density parameter; takes into account angular momenta of preequilibrium and evaporated particles.

Different versions of liquid-drop models (LDM), single-Yukawa modified LDM and Yukawa-plus-exponential modified LDM for fission processes (see [4]) are incorporated (and may be easily selected by an input switch) in the CEM95.

Different empirical formulae for the level density parameter  $a(Z,N,E)$ , and different shell and pairing corrections(see [3]) are incorporated in the CEM95 and may be easily selected by input switches.

For present Intercomparison, calculations for all targets, except O-16, and all incident energies were performed taking into account angular momentum of emitted particles with level densities calculated under the third Iljinov et al. [9] systematics for  $a(Z,N,E)$  (input parameter IFAM=9), with Cameron shell corrections [10] (input parameter ISHA=1), and pairing corrections according to [9] (input parameter CEVAP=12.0). To avoid some purely technical computing troubles, for the light target O-16 calculations were performed with a fixed value for the level density parameter  $a=0.125A$  (input parameters IFAM=1 and AM=0.125) and without taking into account angular momentum of preequilibrium and evaporative particles.

Competition between evaporation and fission of excited compound nuclei was taken into account only for heavy target Au-197. Macroscopic fission barriers by Krappe, Nix, and Sierk [11] (input parameter IB=6), with Cameron [10] shell corrections for g.s. masses (input parameters ISH=1), and Barashenkov et al. [12] corrections for saddle-point masses (input parameter IDELTA=1) for microscopic fission barriers and with Cameron et al. [13] shell corrections (input parameters ISHA=2) in Iljinov et al. third systematics of level density parameters were used for Au-197 target. No dependencies of fission barriers  $B_f$  on angular momentum are taken into account in these calculations (input parameter IJSP=0). For the ratio of level density parameters  $a_f$  and  $a$ , a fixed value of  $a_f/a=1.100$  (input parameter WAM=1.100) was used for all incident energies from 10 MeV to 600 MeV. But to describe the decrease of p-induced Au-197 fission cross section with increasing of proton energy at incident energies about 1 GeV, with a possible minimum at about 2 GeV, which seems to be observed in experiment (see Table 139 in a monograph [6]), I had to fit the ratio  $a_f/a$ , and the values of 1.080, 1.073, 1.064, 1.053, 1.045, and 1.004 for this ratio at proton energies of 1.0, 1.2, 1.6, 2.6, 3.0, and 5.0 GeV were used, correspondingly.

## **7. Range of targets allowed**

The CEM is a statistical model, therefore the CEM95 has not to be used for very light targets like He4. Usually I use the CEM95 for C-12 and heavier targets, though it provides rational results even for Be-targets.

## **8. Range of projectiles allowed**

The CEM95 allows us to calculate only reactions induced by nucleons and pions. But the code can be modified to describe also reactions induced by other projectiles.

## **9. Incident energy regime permitted**



The CEM95 version of the code permits us to calculate reactions for incident energies from about 10 MeV up to several GeV.

## II. Specific Questions:

### 1. How are reaction cross-sections generated in the entrance channel?

The reaction cross-section is calculated by the Monte Carlo method. Its value is equal to the geometrical cross section times the total number of inelastic interactions over the total number of elastic and inelastic simulated events.

### 2. What nuclear density distribution is used, and how does it enter the calculation?

The nuclear matter density is described by the Fermi distribution with two parameters taken from analysis of electron-nucleus scattering:  $c=1.07 \cdot A^{1/3}$  fm, and  $a=0.545$  fm. Practically the nucleus target is divided by concentric spheres into seven zones in every of which the nuclear density is considered to be constant.

### 3. Is the Fermi energy calculated in a local density approximation?

The energy spectrum of nuclear nucleons is estimated in the perfect Fermi gas approximation with the local Fermi energy.

### 4. What nuclear radius parameterization is used?

In the Saxon-Woods distribution of the nuclear density the value  $r_0=1.07$  fm is used; The inverse cross-sections at the pre-equilibrium and compound stages of the reaction are estimated by Dostrovsky et al. approximations [14]. These systematics were fitted with the value  $r_0(\text{eff.})=1.5$  fm for the effective nuclear radius  $R=r_0(\text{eff.}) \cdot A^{1/3}$  in the calculations of Coulomb barriers. The value for  $r_0(\text{eff.})$  is an input parameter (RM) of the CEM95. All calculations for this Intercomparison were performed with a fixed value of this parameter  $RM=1.5$ , though for some medium and heavy nuclei one obtains better agreement with experiment for  $r_0(\text{eff.})=1.4$ , or 1.3 fm. In the CEM95, different models are incorporated to calculate fission barriers. For each concrete model of fission barrier one uses its corresponding values for  $r_0$  (see details in [4]).

### 5. For INC models (For the cascade stage of the reactions)

#### 5.a. What nucleon-nucleon cross sections are used? Are they energy and isospin dependent?

Nucleon-nucleon and pion-nucleon cross-sections are energy- and isospin-dependent and are calculated by the approximation of the experimental data with special polynomial expressions with energy-dependent coefficients given in Ref. [6].

#### 5.b. How is Pauli exclusion handled in the INC?

The Pauli exclusion principle at the cascade stage of the reaction is handled in the following way: One assumes that nucleons of the target occupy all the energy levels up to the Fermi energy. Each of simulated elastic or inelastic interaction of the projectile (or of a cascade particle) with a nucleon of the target is considered as forbidden if "secondary" nucleons have energies smaller than the Fermi energy. If so, a new partner, a new interaction point, and a new interaction mode is simulated for the projectile (or the traced cascade particle) and again the simulated energy of "secondary" nucleons are compared with the Fermi energy for this new point of interaction. This new interaction is again considered as forbidden if the energies of "secondary" nucleons are smaller than the Fermi energy, and so on, until the Pauli principle is kept or until the traced particle leaves the nucleus.

#### 5.c. How are the nuclear density effects treated?

At the beginning of simulation of each event, the nuclear density distributions for protons and neutrons of the target are calculated according to the Saxon-Woods distribution as described

above in point 2. In the CEM95, which uses the standard version of Dubna ICM [6], a further decrease of the nuclear density with emission of cascade particles is not taken into account. Our detailed analysis of different characteristics of nucleon- and pion-induced reactions for targets from C to Am has shown that this effect - the so-called "trawling" of a nucleus may be neglected at incident energies below about 5 GeV. The version of CEM95 used in this Intercomparison does not take it into consideration. But at higher incident energies the progressing decrease of nuclear density with development of intranuclear cascades has strong influence on the calculated characteristics and this trawling effect has to be taken into account [6]. Therefore, to use the CEM95 at incident energies higher than about 5 GeV, the corresponding subroutines used to describe the standard version of Dubna ICM have to be replaced by a version which includes the nonlinear trawling effect of the local reduction of the nuclear density during the development of the cascade [6].

**5.d. How are ejectile binding energies handled?**

In the CEM95, it is assumed that the mean nucleon binding energy at the cascade stage of a reaction is equal to 7 MeV and the pion binding energy is equal to zero (the mean pion potential energy in a nucleus is independent of the radius and pion energy and is equal to 25 MeV).

**5.e. Is any nucleon-cluster scattering considered?**

No nucleon-clusters scatterings are considered.

**5.f. Are ejectiles subject to surface refraction/reflection angular distributions?**

In the standard version of Dubna ICM used in CEM95 the kinetic energy of cascade particles are increased or decreased as they move from one potential region (zone) to another, but their directions remain unchanged. That is, in CEM95 refraction or reflection of cascade nucleons at potential boundaries is neglected.

**5.g. What channels other than neutron and proton are treated e.g. alpha, deuterons, tritons, pi, K, p, etc.?**

In CEM95, at the cascade stage of the reaction only emission of nucleons and pions is considered. (At the preequilibrium and equilibrium stages of the reaction emission of n, p, d, t, He3, and He4 is taken into consideration.)

**5.h. How is the transition made to the next phase of the calculation?**

After the cascade the next phase is the precompound one. In the conventional cascade-evaporation models fast cascade nucleons are traced up to a certain minimal energy, with cut-off energy being about 7-10 MeV below which particles are considered to be absorbed by a nucleus. At the very beginning of the development of the CEM we also used this criterion for the transition from the cascade stage to the precompound one (see Ref. [1]).

In the present version of the CEM it is suggested to use another criterion according to which a primary nucleon and those of second and subsequent generations (if any) are considered as cascade ones, namely the proximity of the imaginary part of the optical potential calculated in the cascade model to the experimental one. This value is characterized by a fixed parameter of the model:  $P=0.3$  [1].

**5.i. What criteria for p-h excitation? is the next phase precompound or compound'?**

The number of captured cascade nucleons and of "holes" produced due to the intranuclear collisions gives for the precompound stage of the reaction the initial particle-hole configuration of the remaining excited nucleus the energy, momentum and angular momentum of which are defined by the conservation laws. The Monte Carlo method of the CEM permits easily to take into account the charge of the excitons, as well.

**6. If there is a precompound phase, describe the PE model used, parameters, i.e., partial state densities, transition rates?**

**Are clusters multiple PE decay, relativistic kinematics used?**

**How are angular distributions computed?**

**Source of inverse cross-sections?**

The preequilibrium and equilibrium stages are considered in the framework of the modified exciton model [17,5]. This model uses effectively the relationship of the master-equation with the markovian random processes. This fact prompts a simple method of solving the related system of master-equation: simulation of the random process by the Monte Carlo technique. In this treatment it is possible to generalize the exciton model to all nuclear transitions with changing the exciton number by +2, -2, and 0, and the multiple emission of particles and to depletion of nuclear states due to particle emission.

We use an equidistant level scheme with the single-particle density  $g$ , Williams formulae [18] corrected for the exclusion principle and indistinguishability of identical excitons in Ref. [19].

The transition rates, are estimated under the assumption that  $M_{+}=M_{-}=M_0=M$  and the value of  $M$  for a given nuclear state is estimated by association of the transition with changing the exciton number by +2 with the probability for quasi-free scattering of a nucleon, which is above the Fermi level on a nucleon of the target nucleus (see [1]).

The emission rates of  $n$ ,  $p$ ,  $d$ ,  $t$ ,  $He_3$ , and  $He_4$  into the continuum are estimated according to detailed balance principle. The inverse cross-sections are taken according to Ref. [14]. For this Intercomparison the binding energies from Ref. [10] are used.

Angular distributions for nucleons emitted at the preequilibrium stage of the reaction are computed in CEM95 from N-N scattering assuming that the nuclear state with given excitation energy  $E$  should be specified not only by the exciton number  $n$  but also by the momentum direction. A corresponding master equation can be generalized for this case provided that the angular dependence for the transition rates is factorized. This calculation scheme is easily realized by the Monte Carlo technique (see [1]). The angular distribution of preequilibrium complex particles is believed to be similar to that for the nucleons in each states. But the angular distribution summed up over all populated nuclear states will certainly differ, because the branching ratio for different particles depends essentially on the decaying nuclear state. Relativistic kinematics was used.

**7. What physics are used for the final de-excitation state: evaporation model, Fermi breakup?**

**Describe parameters used: level densities, inverse cross-sections or transmission coefficient, choice of optical model parameters if relevant (or reference to source), range of excitations allowed, inclusive or exclusive results?**

For the final de-excitation stage is used the evaporation model realized in CEM95 as described in [2]. Different empirical formulae for the level density parameter  $a(Z,A,E)$ , and different shell and pairing corrections are incorporated in the CEM95. The concrete models (input options of the CEM95) used in these calculations are cited above in point 6. At the evaporation stage of reactions the inverse cross-sections are taken according to Ref. [14]. In the CEM there are no limits for the excitation energies of nuclei.

Due to the Monte Carlo method of the CEM the results for all three (cascade, preequilibrium and evaporative) stages of the reaction are exclusive.

**8. Is there any limit as to the number of nucleons from target for which yields may be calculated?**

In the CEM95 there is no limit as to the number of nucleons from target for which yields may be calculated.

**9. Any other comments on aspects not considered in the above questions?**

Almost all calculated with the CEM95 characteristics are histograms. So, e.g., in the calculated spectra are shown not the energies and the angles of the ejectiles but the corresponding intervals for them. To economize the space the beginnings and the ends of the calculated characteristics containing only zeros are not printed.

Besides the requested production cross-sections for all targets and incident energies of this exercise, I calculated also the mean multiplicities, mean energies, yields and production cross sections of all ejected particles, the yields of all residual nuclei, and, for incident energies below 200 MeV, the yields of different modes ("excitation function") contributing to the production of concrete final nuclides.

**10. References to the literature or reports discussing these codes as implemented?**

From the outset this code was developed and applied to describe nucleon-nucleus reactions at intermediate incident energies (see e.g., [1,20]). After that the code was modified and applied to describe stopped negative pion absorption by nuclei [21] and photonuclear reactions [22]. This code has been also widely applied to analyze pion-nucleus interactions at intermediate energies, in particular, to study mechanisms of in-flight pion absorption [23], as well as to investigate the cumulative particle production in interactions of protons, neutrons, pions and photons with nuclei from C to Bi at energies of several tens of MeV up to several GeV [24]. A brief review of physics and possibilities of the CEM95 may be found in Ref. [25]. Currently, the CEM95 is widely used to calculate and analyze different excitation functions for proton-induced reactions at intermediate energies [26].

REFERENCES

1. K.K. Gudima, S.G. Mashnik, and V.D. Toneev, Nucl. Phys., A401 (1983) 329. JINR Communications P2-80-774, P2-80-777, Dubna, 1980 [in Russian].
2. S.G. Mashnik, Izv. Akad. Nauk, Ser. Fiz., 60 (1996) 73 [Bull. Russian Acad. Sci.: Physics, 60 (1996)].
3. S.G. Mashnik, Acta Phys. Slovaca, 43 (1993) 86.
4. S.G. Mashnik, Acta Phys. Slovaca, 43 (1993) 243.
5. S.G. Mashnik and V.D. Toneev, "MODEX - the Progeam for Calculation of the Energy Spectra of Particles Emitted in the Reactions of Pre-Equilibrium and Equilibrium Statistical Decays", Communications of the Joint Institute for Nuclear Research, P4-8417, Dubna, 1974 [Fortran66; text - in Russian].
6. V.S. Barashenkov and V.D. Toneev, "Interaction of High Energy Particles and Nuclei with Atomic Nuclei", Moscow, "Atomizdat", 1972, [in Russian].
7. A.S. Iljinov, "A Code for Intranuclear Cascade Calculation in the Energy Range  $< 5$  GeV," JINR Report B1-4-5478, Dubna, 1970 [Fortran66; text - in Russian].
8. F.G. Gereghi, V.A. Zolotarevsky, K.K. Gudima, S.G. Mashnik, and L.V. Bordianu, "Calculation of Photoneutron Reactions Cross Sections", Report No. 01870081266, Kishinev State University, Kishinev, 1990 [in Russian].
9. A.S. Iljinov, M.V. Mebel et al., Nucl. Phys. A543 (1992) 517.
10. A.G.W. Cameron. Can. J. Phys., 35 (1957) 1021.
11. H.J. Krappe, J.R. Nix, and A.J. Sierk, Phys. Rev. C20 (1979) 992.
12. V.S. Barashenkov, A.S. Iljinov, V.D. Toneev, and F.G. Gereghi, Nucl. Phys. A206 (1973) 131.
13. J.W. Truran, A.G.W. Cameron, and E. Hilf, Proc Int. Conf. on the Properties of Nuclei Far From the Region of Beta-Stability, Leysin, Switzerland, 1970, v. 1, p. 275.
14. I. Dostrovsky, Z. Fraenkel, and G. Friedlander, Phys. Rev. 116 (1959) 683.
17. K.K. Gudima, G.A. Ososkov, and V.D. Toneev, Yad. Fiz. 21 (1975) 260 [Sov. J. Nucl. Phys. 21 (1975) 138].
18. F.C. Williams Jr., Phys. Lett. B31 (1970) 184.
19. I. Ribansky, P. Oblozinsky, and E. Betak, Nucl. Phys. A205 (1973) 545.

20. S.G. Mashnik, Thesis, Lab. Theor. Phys., JINR, Dubna, 1981; K.K. Gudima, S.G. Mashnik, and V.D. Toneev, in: Proc. Europhys. Topical Conf. "Neutron-Induced Reactions", Smolenice, June 21-25, 1982, Phys. and Appl. v.10, 347.
21. S.G. Mashnik, or S.G. Mashnik et al., Revue Roum. Phys. 37 (1992) 179; Sov. J. Nucl. Phys.: 47 (1988) 760 and 47 (1988) 612; Proc.Int.Workshop on Pions in Nuclei, Penyscola, Spain, 3-8 June 1991, "World Scientific, 1992, p. 525; Proc. of the 20th Winter School of the Leningrad Inst. Nucl. Phys., Leningrad, 3 (1985) 236; Sov. Physics-Lebedev Institute Reports 1 (1979) 14; Preprint INR P-0156, Moscow, 1980; in:"Elementary Particle and Atomic Nuclei", Moscow, "Energoatomizdat", 1986, p.60.
22. T. Gabriel, G. Maino, and S.G. Mashnik, JINR Preprint E2-94-424, Dubna, 1994; Proc. XII Int. Sem. on High Energy Probl., Dubna, Russia, 12-17 September, 1994, "World Scientific", Singapore, 1996.
23. S.G. Mashnik, Yad. Fiz. 58 (1995) 1772 [Phys. At. Nucl. 58 (1995) 1672]; Acta Phys. Pol. B24 (1993) 1685.
24. S.G. Mashnik, or S.G. Mashnik et al., Nucl. Phys. A568 (1994), 703; Int. Nuclear Phys. Conf. Beijing, China, August 21-26, 1995, Book of Abstr. p. 5.6-9; Nucl.Phys. A326 (1979) 297; Z. Phys. 312 (1983) 259; Proc. 18th Winter School Leningrad Inst.Nucl.Phys., 3 (1983) 172; Preprint Leningrad Inst. Nucl. Phys. LINP-1302, Leningrad, 1987; Preprint Inst. Appl. Phys. 84-3, Kishinev, 1984; Communications JINR E2-11307, Dubna, 1978.
25. S.G. Mashnik, Proc. 7th Int. Conf. on Nuclear Reaction Mechanisms, Varenna, June 6-11, 1994, p. 100; Proc. Int. Conf. on Nuclear Data for Science and Technology, Gatlinburg, Tennessee, May 9-13, 1994, p. 499; S.G. Mashnik and S.A. Smolyansky, JINR Preprint E2-94-353, Dubna, 1994; in : "Dynamics of Transport in Plasmas and Charged Beams", Eds. G. Maino and M. Ottavani, "World Scientific", Singapore, 1996.
26. Yu.E. Titarenko, S.G. Mashnik, et al. Proc. Int. Workshop on Nucl. Methods of Transmutation of Nuclear Wastes: Problems, Perspectives, Cooperative Research, Dubna, Russia, May 29-31, 1996; Proc. II Int. Conf. on Accelerator-Driven Transmutation Technologies and Applications, Kalmar, Sweden, June 3-7, 1996 (in press); O. Bersillon, T. Gabriel, and S.G. Mashnik, "Cascade-Exciton Model Detailed Analysis of Proton Spallation at Energies from 10 MeV to 5 GeV," NEA OECD Report, Issy-les-Moulineau, France, 1996 (in press).

## 6

## HETC-FRG

### Code Information Questionnaire

#### I. General Questions:

1. Name of the code

HETC-FRG

2. Name of the participant

K. Ishibashi, N. Shigyo

3. Responsible author of the code

K. Ishibashi

4. Reference of the code

P. Cloth et al., HERMES, High Energy Radiation Monte Carlo Elaborate System, KFA-IRE-E AN/12/88 (1988).

5. Is a manual available?

To be prepared to Memoirs of the Faculty of Engineering Kyushu

6. What nuclear reaction models are contained?

Intranuclear cascade

Precompound decay

Fragmentation process based on liquid-gas phase transition model

Evaporation - Weisskopf-Ewing

Fermi statistics

Fission model

Statistical model

Empirical formulas are used as far as possible (F. Atchison)

7. Range of targets allowed

$A = 1$  and  $4 \leq A \leq 239$

8. Range of projectiles allowed

$1 \leq A \leq 20$

9. Incident energy regime permitted

$0 < E < 1$  TeV

#### II. Specific Questions:

1. How are reaction cross-sections generated in the entrance channel?

The geometrical cross section is multiplied by ratio of numbers of reaction to total (reaction + pseud) of incident particles.

2. What nuclear density distribution is used, and how does it enter the calculation?

3-step functions.

$$\rho_i = \alpha_i \cdot \rho(0)$$

where  $i$  is the region number,  $\alpha_i$  is the factor for the region  $i$  and  $\rho(0)$  is the normal density.

**3. Is the Fermi energy calculated in a local density approximation?**

yes

**4. What nuclear radius parameterization is used?**

$$r = r_1 * A^{1/3}$$

$$r_1 = 1.07 * 10^{-13} \text{ cm}$$

**5. For INC models**

**5.a What nucleon nucleon cross sections are used? Are they energy and isospin dependent?**

G.Q. Li and R. Machleidt [1] energy dependent model.

**5.b How is Pauli exclusion handled in the INC?**

$$F = \int_{\Omega} \frac{d}{d\Omega} d\Omega$$

where  $\Omega$  is the solid angle of the Fermi surface.

**5.c How are the nuclear density effects treated?**

Nucleon-nucleon collision cross section depends on the nuclear density. mean free path is obtained by nuclear density and nucleon-nucleon cross section.

**5.d How are ejectile binding energies handled?**

7 MeV fixed for all ejectiles.

**5.e Is any nucleon-cluster scattering considered?**

No.

**5.f Are ejectiles subject to surface refraction/reflection angular distributions?**

No.

**5.g What channels other than neutron and proton are treated e.g. alpha, deuterons, pi, K, p, etc.?**

$$\pi^+, \pi^-, \pi^0, \mu^+, \mu^-$$

**5.h How is the transition made to the next phase of the calculation?**

under cut-off energy (15 MeV).

**5.i What criteria for p-h excitation? Is the next phase precompound or compound?**

p-h excitation not considered.

- 6. If there is a precompound phase, describe the PE model used, parameters, i.e., partial state densities, transition rates? Are clusters multiple PE decay, relativistic kinematics used? How are angular distributions computed? Source of inverse cross-sections?**

Fragmentation based on liquid-gas phase transition model [2]. Transition rates are obtained by excitation energy after cascades. No relativistic model. Angular distribution is isotropic in the moving frame.

- 7. What physics are used for the final de-excitation state: evaporation model, Fermi breakup? Describe parameters used: level densities, inverse cross-sections or transmission coefficient, choice of optical model parameters if relevant (or reference to source), range of excitations allowed, inclusive or exclusive results?**

Evaporation model. Level density is a function of mass and atomic number. Inverse Cross section is from Dostrovsky's empirical equation.

- 8. Is there any limit as to the number of nucleons from target for which yields may be calculated?**

No.

- 9. Any other comments on aspects not considered in the above questions?**

No.

- 10. References to the literature or reports discussing these codes as implemented?**

[1] G.Q. Li and R. Machleidt, Phys. Rev.**C48** (1993) 1702; Phys. Rev.**C49** (1994) 566.

[2] N. Shigyo et al., J. Nucl. Sci. Technol**32** (1995) 1; JAERI-Conf. 95-0008 (1995) 217.



**Code Information Questionnaire****I. General Questions:****1. Name of the code**

INUCL

**2. Name of the participant**

Vladimir D. Kazaritsky and ?.?. Vyacheslav

**3. Responsible author of the code**

Nikita Stepanov

**4. Reference of the code**

N. Stepanov Ph.D. thesis, ITEP, Moscow, 1990

**5. Is a manual available?**

no

**6. What nuclear reaction models are contained?**

Intranuclear cascade,  
Precompound decay (exiton master equation)  
Evaporation (Weisskopf - Ewing)  
Fission (phenomenological model, incorporating some features of the fission statistical model)

**7. Range of targets allowed**

arbitrary.

**8. Range of projectiles allowed**

p,n,pi and nuclei.

**8. Incident energy regime permitted****II. Specific Questions:**

From a few Mev to 10 GeV for n,p,pi and up to about 100 MeV/nucleon for nuclei.

**1. How are reaction cross-sections generated in the entrance channel?**

Total inelastic cross section has to be taken from outside to normalize all data. Total reaction cross-sections [mbarn] were calculated by J.R. Letaw's formulae:

$$45 * A^{**0.7} * (1 + 0.016 * \sin(5.3 - 2.63 * \log_{10}(A)))^{**} (1 - 0.62 * \exp(-E/200) * \sin(10.9 * E^{**}(-0.28)))$$

Ref.: S. Pearlstein, The Astrophysical Journal, 346: 1049-1060, 1989 November 15

**2. What nuclear density distribution is used, and how does it enter the calculation?**

Nuclear density distribution are derived from the  $\text{Re}(V_{\text{opt}})$  distribution.  
In cascade part, nucleus is divided into a finite number of zones with constant density.

**3. Is the Fermi energy calculated in a local density approximation?**

Generally speaking, Yes (see 2.)

**4. What nuclear radius parameterization is used?**

By the definition  $R(A)$  is derived from eq.  $\text{Den}(R(A)) = 0.01 * \text{Den max}$

**5. For INC models**

**5.a. What nucleon nucleon cross-sections are used? Are energy and isospin dependent?**

Parametrizations based on the experimental data (ED) are used. They are energy and isospin dependent. ED available before 1980 are used only. The parameterizations described in ([1] Barashenkov V.S., Toneev V.D. High Energy interactions of particles and nuclei with nuclei. Moscow, 1972 (in Russian, but there is an English translation)) are used.

**5.b. How is Pauli exclusion handled in the INC?**

Simulated particle-particle interaction is accepted only for secondary nucleons which have  $E_n > E_f$ .

**5.c. How are nuclear density effects treated?**

Densities are recalculated after each step, but not other parameters.

**5.d. How are ejectile binding energies handled?**

For nucleons binding energies are calculated using mass formula. For pions  $V_{\text{opt}}$  is taken to be constant (about 7 MeV).

**5.e. Is any nucleon-cluster scattering considered?**

Not yet, except pion absorption.

**5.f. Are ejectiles subject to surface refraction/reflection angular distributions?**

Yes (see 2.).

**5.g. What channels other than neutron and proton are treated e.g. alpha, deuterons, tritons,  $\alpha$ , K, p, etc.?**

**5.h. How is the transition made to the next phase of the calculation?**

Cascade is stopped when all the particles, which can escape the nucleus, do it.  
Then conformity with the energy - conservation law is checked and the given event is accepted, if  $E(\text{excitation}) > E_{\text{cut}} \sim$  a few MeV.

**5.i. What criteria for p-h excitation? is the next phase precompound or compound'?**  
**Only pions.**

The next phase is precompound. Initial conditions are defined during the cascaded phase: p - number of "particles", i.e. nucleons, which can not escape the nucleus and have too small interaction probability; h - number of "holes" = number of nuclear nucleons involved in the cascade; energy - momentum of the exciton system derived from the conservation law.

**6. If there is a precompound phase, describe the PE model used, parameters, i.e., partial state densities, transition rates?**

Main parameters are taken from (Ribansky I. et al, Nucl.Phys.,1973, A205, p.545 (level densities); Kolbach.C., Z.Phys.,1978, A287, p.319 (matrix elements)).

Only  $N \rightarrow N$ ,  $N \rightarrow N + 2$ ,  $N \rightarrow N - 2$ ,  $N \rightarrow N - 1$  channels are treated. The angular distribution is isotropic in the frame of rest of the exciton system.

**Are clusters multiple PE decay, relativistic kinematics used?**

**How are angular distributions computed?**

**Source of inverse cross-sections?**

**7. What physics are used for the final de-excitation state: evaporation model?**

**Describe parameters used: level densities, inverse cross-sections or transmission coefficient, choice of optical model parameters if relevant (or reference to source), range of excitations allowed, inclusive or exclusive results?**

Weisskopf-Ewing evaporation in competition with fission. Emissions of n,p,d,t,He3,He4,gamma is allowed. Level densities derived from exp.data are used. Angular momentum and spin dependence are not included. Other parameters are the same as in ([1], see 5a.) Fermi breakup is allowed only in some extreme cases, i.e. for light nuclei and  $E(\text{excitation}) > 3 \cdot E_b$ . Only the total nucleus decay into neutrons and protons is treated.

**8. Is there any limit as to the number of nucleons from target for which yields may be calculated?**

Generally speaking, no.

**9. Any other comments on aspects not covered in the above questions?**

INUCL is designed as a particle - nucleus interaction simulation block for the particle - target interaction simulation program PHOENIX. It produces an exclusive approach to simulating events with reasonable performance.

**10. References to the literature or reports discussing these codes as implemented?**

Shvedov.O.V. et al, Preprint ITEP 81-93, Moscow, 1993 (the most recent one).

## Code Information Questionnaire

**I. General Questions:****1. Name of the code**

ISABEL-EVA

**2. Name of the participant**

Zeev Fraenkel

**3. Responsible author of code:**

Zeev Fraenkel

**4. Reference for the code:**

Phys.Rev.166, 1305 (1968)

Phys.Rev. C8, 581 (1973)

Phys.Rev. C20, 2227(1979)

Phys.Rev. C24, 488 (1981)

Phys.Rev.116, 683 (1960)

**5. Is a manual available?**

NO

**6. What nuclear reaction models are contained?**

-intranuclear cascade: YES

-precompound decay: NONE

-evaporation: Weisskopf-Ewing

-Fission model: Bohr-Wheeler

**7. Range of targets allowed:**

A&gt;16

**8. Range of Projectiles:**

protons, pions, heavy ions.

**9. Incident energy regime permitted:**

100MeV &lt; E/A &lt; 1000MeV

**VI.2 Specific Questions:****1. How are reaction cross-sections generated in the entrance channel?**

total # of cascades - transparencies

----- \* geometric cross section

total # of cascades calculated

**2. What nuclear density distribution is used:**

an 8-step density distribution approximating the Hofstadter distribution.

**3. Is the Fermi energy calculated in a local density approximation:**

YES

**4. What nuclear radius parametrization is used:**

Half-Density-Radius =  $1.07 \cdot (A^{1/3})$  Fm

**5. For INC models:**

**5.a. cross section tables for total cross sections & angular distributions**

BOTH ENERGY AND ISOSPIN DEPENDENT.

**5.b. How is Pauli exclusion handled in the INC:**

The particle energy is not allowed to fall below the (local) Fermi energy.

**5.c. How are nuclear density effects treated:**

the particle energy changes according to the change in Fermi energy as the particle enters a different density region. there are two OPTIONS AVAILABLE: 1) THE PARTICLE MAY BE REFRACTED OR REFLECTED, i.e. the RADIAL part of its momentum is changed WITHOUT changing its tangential momentum. 2) NO refraction/reflection, i.e. the particle energy is changed when the particle enters a new density region but its direction is NOT changed.

**5.d. How are ejectile binding energies handled:**

a fixed energy is subtracted from the emitted particle. the total excitation energy of the residual nucleus is calculated on the basis of nuclear mass tables.

**5.e. Is any nucleon-cluster scattering considered?**

NO

**5.f. are ejectiles subject to surface refraction/reflection angular distributions?**

Both options available, see 5c.

**5.g. In INC part of calculations, only nucleons and pions are considered.**

IN THE EVAPORATION PART P,N,D,TRITON,HE3,HE4 EVAPORATION IS INCLUDED as a standard. Heavier ions may be included if desired.

**5.h. How is the transition made to the next phase of the calculation?**

The INC phase of the calculation stops when none of the remaining PARTICLES IN THE NUCLEUS HAVE ENOUGH ENERGY TO ESCAPE FROM IT. At this stage the nucleus is considered an excited equilibrated 'compound nucleus' of given A,Z,excitation energy and angular momentum and these data represent the input for the second part of the calculation (see below).

**5.i. What criteria for p-h excitation?**

NOT CONSIDERED

**is the next phase precompound or compound?**

COMPOUND

- 6. If there is a precompound phase, describe the PE model used, parameters, i.e., partial state densities, transition rates?**

not relevant (no pre-equilibrium phase)

- 7. What physics is used for the final de-excitation stage?**

EVAPORATION MODEL.

the level density parameter is an input parameter.

the inverse cross sections are simple parametrisations of the continuum cross-sections. gamma competition is neglected.

the excitation energy range is not restricted by the program but rather by the range of validity of the Weisskopf theory. these theoretical considerations also limit the validity of the program to nuclei heavier than about  $A=16$ .

- 8. Is there any limit as to the number of nucleons from target for which yields may be calculated?**

none except for the limitations mentioned in 7.

- 9. Any other comments on aspects not covered in the above questions?**

none

- 10. References to the literature or reports discussing these codes implemented?**

see VI.1.4.

**Code Information Questionnaire****I. General Questions:****1. Name of the code**

combination of ISABEL (isobar) with SMM

**2. Name of the participant**

Hans-Jürgen Lange

**3. Responsible author of the code**

ISABEL: Zeev Fraenkel  
SMM: Alexandre Botvina

**4. Reference of the code**

ISABEL: see ISABEL contribution by Zeev Fraenkel  
SMM: A. S. Botvina, I. N. Mishustin, Phys. Lett. B 294 (1992) 23-26

**5. Is a manual available?**

no

**6. What nuclear reaction models are contained?**

ISABEL: intranuclear cascade  
SMM: statistical multifragmentation  
evaporation (Weisskopf-Ewing)  
fission

**7. Range of targets allowed**

No restrictions by authors, but restrictions due to statistical assumptions.

**8. Range of projectiles allowed**

hadrons and hadron clusters

**9. Incident energy regime permitted**

200 MeV-10 GeV

**II. Specific Questions:****1. How are reaction cross-sections generated in the entrance channel?**

geometric cross sections

**2. What nuclear density distribution is used, and how does it enter the calculation?**

volume of nucleus divided in eight shells, see also ISABEL contribution by Zeev Fraenkel

**3. Is the Fermi energy calculated in a local density approximation?**

local Thomas Fermi density approximation for momenta, see also ISABEL contribution by Zeev Fraenkel

**4. What nuclear radius parameterization is used?**

see ISABEL contribution by Zeev Fraenkel

**5. For INC models**

see ISABEL contribution by Zeev Fraenkel

**6. If there is a precompound phase, describe the PE model used, parameters, i.e., partial state densities, transition rates?**

no

**Are clusters multiple PE decay, relativistic kinematics used?**

**How are angular distributions computed?**

**Source of inverse cross-sections?**

**7. What physics are used for the final de-excitation state: evaporation model?**

**Describe parameters used: level densities, inverse cross-sections or transmission coefficient, choice of optical model parameters if relevant (or reference to source), range of excitations allowed, inclusive or exclusive results?**

for detailed description of last step see SMM-publications above

**8. Is there any limit as to the number of nucleons from target for which yields may be calculated?**

no

**9. Any other comments on aspects not covered in the above questions?**

no

**10. References to the literature or reports discussing these codes as implemented?**

no



**Code Information Questionnaire****I. General Questions:****1. Name of the code**

PACE-MSM

**2. Name of the participant**

Olga Vladilenovna Fotina

**3. Responsible author of the code**

Olga Vladilenovna Fotina

**4. Reference of the code**

Description of using MSM model is, for example, in ref. (1): D.O.Eremenko, O.V.Fotina et al., in: Intermediate Energy Nuclear Data: Models and Codes, Proceedings of Specialists' meeting, ISSY-les-Moulineaux,(France) 30 May - 1 June 1994, OECD, Paris,1994, p.287.

**5. Is a manual available?**

Description presented in code.

**6. What nuclear reaction models are contained?**

Reaction cross sections generated in the entrance channel by our own approximation expressions (see ref.(\*)).

Instead of use of the intranuclear cascade model and precompound models we used estimations in the frame of Moving Source model (MSM); see ref.(1) for preequilibrium particles (neutron and proton).

Evaporation - Hauser-Feshbach formalism, realized in widely used code PACE (this is a modified version of JULIAN - the Hillman-Eyal evaporation Monte-Carlo code coupling angular momentum. )

A default level density is taken from Gilbert and Cameron. The fermi-gas level density parameter 'a' can alternatively be taken as A/const. The yrast line of Gilbert-Cameron can be replaced by the Cohen-Plasil-Swiatecki yrast line.

Fission is also considered as a decay mode, if the fission barrier at the angular momentum considered is less than 40 MeV. This cutoff level can be changed in the program.

The default fission barrier is the Cohen-Plasil-Swiatecki rotating liquid drop fission barrier. The saddle point level density is the ground state level density m.b. exponentiated to SQRT (ARATIO).

**7. Range of targets allowed**

Range of targets allowed of A from 20 up to 250 (determined by MSM model).

**8. Projectiles and energy regime**

Only protons are allowable as projectiles. This connected with the supplied version of MSM model. In the case of dominating of evaporation processes the code PACE has not restrictions for calculations of evaporation processes.

## **9 Projectiles and energy regime**

The proton energy range is from 100 MeV up to 1000 MeV.

For evaporation processes the code PACE has excitation energy limitations near 300 MeV, that connected with computing limitations.

## **II. Specific Questions:**

- 1. How are reaction cross-sections generated in the entrance channel?**
- 2. What nuclear density distribution is used, and how does it enter the calculation?**
- 3. Is the Fermi energy calculated in a local density approximation?**
- 4. What nuclear radius parameterization is used?**
- 5. For INC models**
- 6. If there is a precompound phase, describe the PE model used, parameters, i.e., partial state densities, transition rates?**

**Are clusters multiple PE decay, relativistic kinematics used?**

**How are angular distributions computed?**

**Source of inverse cross-sections?**

- 7. What physics are used for the final de-excitation state: evaporation model?**  
**Describe parameters used: level densities, inverse cross-sections or transmission coefficient, choice of optical model parameters if relevant (or reference to source), range of excitations allowed, inclusive or exclusive results?**
- 8. Is there any limit as to the number of nucleons from target for which yields may be calculated?**
- 9. Any other comments on aspects not covered in the above questions?**
- 10. References to the literature or reports discussing these codes as implemented?**

**Code Information Questionnaire****I. General Questions:****1. Name of the code**

MSDM - Many Stage Dynamical Model

**2. Name of the participant**

A.S. Botvina, A.V. Dementyev, O.N. Smirnova, N.M. Sobolevsky, V.D. Toneev

**3. Responsible author of the code**

N.S. Amelin - string model of hadron-hadron interaction  
 K.K. Gudima, V.D. Toneev - cascade, coalescence and pre-equilibrium stages of the reaction  
 Joint Institute for Nuclear Research, Dubna

A.S. Botvina - equilibrium deexcitation stage of the reaction  
 N.M. Sobolevsky - some interface programs  
 Institute for Nuclear Research of Russian Academy of Science, Moscow

**4. Reference for the code**

Answer to Specific Question 10.

**5. Is a manual available?**

No

**6. What nuclear reaction models are contained?**

- Intranuclear cascade (including nucleus-nucleus interaction)
- Coalescence
- Precompound decay; exciton master equation
- Evaporation; Weisskopf-Ewing
- Fermi statistics
- Fission model
- Multifragmentation of highly excited nuclei

**7. Range of targets allowed**

Unlimited

**8. Range of projectiles allowed**

Nucleons, pions, kaons, antinucleons, nuclei

**9. Incident energy regime permitted**

Up to 500 GeV (per nucleon)

Note: MSDM was used as hadron-nucleus generator of the transport code SHIELD at the thick target benchmark NSC/DOC(95)2. A.V.Dementyev, N.M.Sobolevsky. SHIELD - a Monte Carlo Hadron Transport Code. Inter-mediate Energy Nuclear Data: Models and Codes, Proc. of Specialists' Meeting, 30 May - 1 June 1994, OECD, Paris, 1994.

## II Specific Questions:

### 1. How are reaction cross-sections generated in the entrance channel?

Cross section is calculated as  $\sigma_{\text{geom}} * \eta_{\text{tr}}$  where the transparency factor  $\eta_{\text{tr}} = N_{\text{in}} / (N_{\text{in}} + N_{\text{el}})$  with  $N_{\text{el}}$  is a number of events when a projectile has passed through without collisions.

### 2. What nuclear density distribution is used and how do these enter the calculation?

The nuclear matter density is described by the Fermi distribution with parameters  $c = 1.07 * A^{1/3}$  fm,  $a = 0.545$  fm. For light nuclei ( $A < 12$ ) the Gaussian distribution is used with individual values of parameter for each A.

### 3. Is the Fermi energy calculated in a local density approximation?

Yes.

### 4. What nuclear radius parameterization is used?

The average nucleus radius  $R = 1.3 * A^{1/3}$  but the maximal interaction radius is defined by the point where the nuclear density is decreased by 20 as compared to the density at center of a nucleus.

### 5. For INC models:

#### 5.a. What nucleon nucleon cross-sections are used? Are energy and isospin dependent?

The hadron-nucleon cross sections are energy- and isospin-dependent and are calculated by approximations of experimental data [1] (at low energies up to several GeV). At high energy the cross sections for different channels are calculated on a basis of Quark-Gluon String Model (QGSM) [3,5]. The coherence of the cross sections in the transition energy region is provided.

#### 5.b. How is Pauli exclusion handled in the INC?

It is assumed that nucleons in the nucleus-target occupy all energy levels up to Fermi energy. Any elastic or inelastic interaction of some cascade particle with intranuclear nucleon is considered as forbidden if secondary nucleon has energy below the Fermi energy.

#### 5.c. How are nuclear density effects treated?

The nucleus is treated as a collection of separate nucleons rather than a drop of continuous matter. At the beginning of simulation of each hadron-nucleus interaction the intranuclear nucleons are distributed according to appropriate nuclear matter density (see item 2). The decrease of nuclear density due to knocking nucleons out of the nucleus during the cascade process is taken into account.

#### 5.d. How are ejectile binding energies handled?

The nucleon binding energy is equal to 7 MeV at the cascade stage of the reaction for all target nuclei.

#### 5.e. Is any nucleon-cluster scattering considered?

No.

#### 5.f. Are ejectiles subject to surface refraction/reflection angular distributions?

No, as no inner surfaces are used at nuclear density description.

**5.g. What channels other than neutron and proton are treated e.g. alpha, deuterons, tritons, pi, K, p, etc.?**

Projectiles are nucleons, pions, kaons, antinucleons etc. (altogether almost 70 hadrons as QGSM [3,5] considers two lowest SU(3) multiplets in mesonic, baryonic and antibaryonic sector) as well as any nuclei beginning with deuterons.

**5.h. How is the transition made to the next phase of the calculation?**

After cascade stage the following characteristics of the residual nucleus are known: A and Z, excitation energy, momentum, angular momentum, particle-hole configuration. Therefore one can simulate further pre-equilibrium and/or equilibrium stages of the reaction.

**5.i. What criteria for p-h excitation? is the next phase precompound or compound?**

The number of captured cascade nucleons and of "holes" produced due to the intranuclear collisions gives the initial particle-hole configuration for simulation of precompound stage.

**6. If there is a precompound phase, describe the PE model used, parameters, i.e. partial state densities, transition rates? Are clusters treated multiple PE decay, relativistic kinematics used? How are angular distributions computed? Source of inverse cross-sections?**

Precompound stage of the reaction is described by means of Monte Carlo solution of the master equation [6]. The emission of n, p, d, t, He3, and He-4 is considered at relativistic kinematics. The inverse cross sections are taken according to I. Dostrovsky et al.. A single particle equidistant level density scheme with the Pauli correction is used. Anisotropy of angular distributions arises due to the recoil nucleus momentum is attributed to the exciton system only rather than to all nucleons.

**7. What physics are used for the final de-excitation stage: evaporation model, Fermi breakup? Describe parameters used: level densities inverse cross-sections or transmission coefficient, choice of optical model parameters if relevant (or reference to source), range of excitations allowed, inclusive or exclusive results?**

Light ( $A < 16$ ) excited nuclei undergo explosive Fermi break-up [7,8]. The way of deexcitation of more heavy nuclei depends on the value of excitation energy  $E^*$ . At relatively small excitation energy ( $E^*/A < 2$  MeV) the nucleus suffer traditional evaporation/fission process [8-11]. When  $E^*/A > 2$  MeV the multifragmentation of the nucleus occurs [8,10,12] giving several excited nuclear fragments (in average 2 - 4 as a rule). In the following these fragments undergo the successive particle evaporation/fission or Fermi break-up in dependence on A. Physically this process is a manifestation of liquid-gas type phase transition in finite nuclei. Thus the Many Stage Model provides exclusive description of the nuclear reaction to the full extent.

**8. Is there any limit as to the number of nucleons from target for which yields may be calculated?**

No.

**9-10. Any other comments on aspects not covered in the above questions?**

References to the literature or reports discussing these codes as implemented?

See below "The Model Description" and References herein.

**The model description**

Our description of nuclear reactions is based on the **Many Stage Model** (MSDM) combining together several approaches and being tested on a large variety of hadron-nucleus and nucleus-nucleus collisions in a wide range of the beam energy: from about 15 MeV till few hundreds of GeV. We assume that the interaction process proceeds through the following subsequent stages:

fast **cascade** stage which reduces the projectile-target interaction at a serie of binary collisions between nuclear constituents and/or produced hadrons; **coalescence** stage followed by the cascade one at which cascade baryons can form a complex particle due to the final state interaction; **pre-equilibrium** stage of residual nuclei when a nucleus is getting equilibrated (thermalized) and some particles can be emitted during this equilibration process; **equilibrated de-excitation** stage of a nucleus which is followed by the pre-equilibrium particle emission and can be realized in a competing way via **Fermi decay**, subsequent particle-fragment **evaporation**, nuclear **fission** or **multifragmentation** process.

### Cascade stage

For energies below 600 MeV when it is possible to limit our consideration by only nucleons, pions and deltas, we use the *Dubna Cascade Model*] (DCM) [1] extended to proper describing pion dynamics for production and absorption processes [2]. DCM is based on the Monte-Carlo solution of a set of the Boltzmann-Uehling-Uhlenbeck relativistic kinetic equations which are treated exactly for the collision term (including cascade-cascade interactions) but in an approximate way for the mean-field evolution.

We keep the scalar nuclear potential of the initial state, defined in the Thomas-Fermi approximation, and change only the nuclear potential depth according to a number of knocked-out nucleons. This allows one to take into account nuclear binding and Pauli principle [1].

This approximation is rather good for hadron-nucleus or peripheral nucleus-nucleus collisions where there is no large disturbance of the mean field but it is less justified for violent central collisions of heavy ions.

At energies higher than about 10 GeV, the *Quark-Gluon String Model* (QGSM) is used [3]. This model for hadron collisions is based on the  $1/N_c$  expansion of the amplitude for binary processes where  $N_c$  is a number of quark colors. Different terms of the  $1/N_c$  expansion correspond to different diagrams which can be classified through their topological properties. Every diagram defines how many strings are created in a hadronic collision and which quark-antiquark or quark-diquark pairs form these strings. The relative contributions of different diagrams can be estimated within the Regge theory, and all QGSM parameters for hadron-hadron case were found from the Regge-like analysis of experimental data. The break-up of strings via creation of quark-antiquark and diquark-antidiquark pairs is described by means of the Field-Feynman method [4] using phenomenological functions for the fragmentation of quarks, antiquarks and diquarks into hadrons. This hadronic input is used for QGSM of nuclear collisions which, in its turn, is based on the modified non-Markovian relativistic kinetic equation having a structure close to the Boltzmann-Uehling-Uhlenbeck kinetic equation but accounting of the finite formation time for newly created hadrons (or string evolution) [3].

The above noted two energy extremes were bridged by the QGSM extention downward in the beam energy [5]. Thus, QGSM is applied really to nuclear interactions in the whole energy range above 600 MeV.

One should note that QGSM considers two lowest SU(3) multiplets in mesonic, baryonic and antibaryonic sectors, so interactions between almost 70 hadrons are treated on the same footing. This is a great advantage of this approach and quite important for the proper consideration of both abundancy of hadrons, their decays and even properties of excited residual nuclei [3, 5].

Coalescence stage: By the end of the cascade stage, nucleons which are close each to other in the momentum space can coalesce to form a complex particle. In our treatment following [1], this coalescence is made for every nuclear event looking for a possible formation of fast d, t,  $^3\text{He}$  nuclei and  $\alpha$  particles.

Pre-equilibrium decay stage: A residual nucleus resulting from the cascade stage is not in equilibrium state, as a rule. Further evolution of this nucleus towards equilibrium is described in terms of the pre-equilibrium model based on the Monte-Carlo solution of the corresponding

master-equation [6]. Transition matrix elements are estimated from interaction cross sections. Complex particle emission and anisotropy of angular distributions for pre-equilibrium particles are taken into account. The initial state is given by the cascade stage calculation results [1, 6].

Equilibrium decay stage: After cascade and pre-equilibrium stages of the reaction we have an ensemble of excited thermalized nuclei which undergo a slower disintegration.

For excited light (with  $A \leq 16$ ) nuclei, even a relatively small excitation energy may be comparable with their total binding energy. In this case, the principal mechanism of de-excitation is the explosive decay of the excited nucleus into several smaller clusters. To describe this process the *Fermi model* [7] is used. All final-state fragments are assumed to be in their ground or low excited states. We have slightly modified this model [8] by including fragment excited states stable with respect to the nucleon emission as well as long-lived unstable nuclei  ${}^5\text{He}$ ,  ${}^5\text{Li}$ ,  ${}^8\text{Be}$ ,  ${}^9\text{Be}$ , which decay at the final stage of nuclear expansion. The number of channels considered was about  $10^6$  for  ${}^{16}\text{O}$  nucleus and  $2 * 10^6$  for  ${}^{12}\text{C}$ .

At relatively small excitation energy  $E^* < 2$  MeV/nucleon) the intermediate and heavy nuclei ( $A > 16$ ) suffer *successive particle evaporation* or undergo *fission*. For description of these process we use a version of evaporation-fission models developed in [8, 9, 10]. The standard Weisskopf evaporation scheme was modified to take into account, among with light particles (nucleons, d, t,  $\alpha$ ), the heavier ejectiles up to  ${}^{18}\text{O}$  in ground and particle-stable excited states [8].

The process of fission competes with particle emission. Following the Bohr-Wheeler statistical approach it was assumed that the partial width for the compound nucleus fission is proportional to the level density at the saddle point  $\rho_{\text{sp}}(E)$  and entering here the height of the fission barrier was is determined by the Myers-Swiatecki prescription [11]. Approximation of  $\rho_{\text{sp}}(E)$  were checked by the analysis of nuclear fissibility and  $\Gamma_n/\Gamma_f$  branching ratios. The influence of the shell structure on the level densities is disregarded since in the analyzed reactions we are usually dealing with a broad distribution in excitation energy and isotope content of thermalized nuclei, therefore the shell effects are expected to be washed out.

At high excitation energy the main de-excitation mechanism of the excited nuclei is a many-particle break-up or multifragmentation. For simulating nuclear disintegration into many fragments we use statistical multifragmentation model (SMM) described in [8, 10, 12] where all details and parameter values can be found. The break-up channels are simulated by the Monte-Carlo method according to their statistical weights. After break-up of the system, the fragments propagate independently in their mutual Coulomb fields and undergo secondary decays. The de-excitation of large ( $A_f > 16$ ) fragments is described by the above mentioned evaporation-fission model and, for smaller fragments, by the Fermi break-up model. The correct description of the multifragmentation process is quite important for calculating the fragment production already at excitation energies more than  $E^*/A \sim 2-3$  MeV.

#### References:

- [1] V.D.Toneev, K.K.Gudima, Nucl. Phys **A400** (1983) 173c.
- [2] P. Danielewicz, G.F. Bertsch, Nucl. Phys **A533** (1991) 172.
- [3] N.S.Amelin, K.K.Gudima, V.D.Toneev, "Nuclear Equation of State, Part B: QCD and the Formation of the Quark-Gluon Plasma", Eds. W.Greiner, H.Stöcker, Plenum Press, 1989, p.473; V.D. Toneev, N.S. Amelin, K.K. Gudima, S.Yu. Sivoklovov. Nucl. Phys. **A519** (1990) 463c; N.S. Amelin, E.F. Staubo, L.S. Csernai et al. Phys. Lett. **B261** (1991) 352; Phys.Rev. **C44** (1991) 1541; Phys.Rev.Let **67** (1991) 1523.
- [4] R.D. Field, R.P. Feynman, Nucl. Phys **B136** (1978) 1.
- [5] N.S. Amelin, K.K. Gudima, S.Yu. Sivoklovov, V.D. Toneev, Sov. Jour. of Nucl. Phys. **52** (1990) 272; V.D. Toneev, K.K. Gudima, Preprint GSI-93-52, Darmstadt, 1993.
- [6] K.K. Gudima, G.A. Ososkov, V.D. Toneev, Sov. Journ. of Nuclear Phys. **21** (1975) 260; K.K. Gudima, S.G. Mashnik, V.D. Toneev, Nucl. Phys **A401** (1983) 329.
- [7] E. Fermi, Progr. Theor. Phys **5** (1950) 570.
- [8] A.S. Botvina, A.S. Iljinov, I.N. Mishustin et al., Nucl.Phys **A475** (1987) 663.

- [9] G.D. Adev, A.S. Botvina, A.S. Iljinov, M.V. Mebel, N.I. Pischasov and O.I. Serduk, Preprint INR, 816/93, Moscow, 1993.
- [10] J.P. Bondorf, A.S. Botvina, A.S. Iljinov, I.N. Mishustin and K. Sneppen. Physics Reports **257** (1995) 133-221.
- [11] W.D. Myers and W.J. Swiatecki, Nucl. Phys. **81** (1966) 1.
- [12] A.S. Botvina, A.S. Iljinov and I.N. Mishustin, Nucl.Phys. **A507** (1990) 649.



**Code Information Questionnaire****I. General Questions:****1. Name of the code**

CASCADE

**2. Name of the participant**

Yu.N.Shubin, A.Yu.Konobeyev, V.P.Lunev

**3. Responsible author of the code**

V.S.Barashenkov

**4. Reference for the code**

Ref.[1]

**5. Is a manual available?**

Yes.

**6. What nuclear reaction models are contained?**

Intranuclear cascade model with explicit consideration of the time coordinate described in Ref.[2], evaporation model, fission model.

**7. Range of targets allowed**

Unrestricted.

**8. Range of projectiles allowed**

Unrestricted.

**9. Incident energy regime permitted**

Up to 1 TeV.

**VI.2. Specific Questions:****1. How are reaction cross-sections generated in the entrance channel?**

Reaction cross-sections are obtained using the experimental and evaluated data from Ref.[3].

**2. What nuclear density distribution is used and how do these enter the calculation?**

Nuclear distribution obtained from experimental electron-nuclei scattering data is used.

**3. Is the Fermi energy calculated in a local density approximation?**

Yes.

**4. What nuclear radius parameterization is used'?**

**5. For INC models:**

**5.a. What nucleon nucleon cross-sections are used? Are energy and isospin dependent?**

Nucleon-nucleon cross-sections are energy and isospin dependent.

**5.b. How is Pauli exclusion handled in the INC?**

**5.c. How are nuclear density effects treated?**

Nonuniform nuclear density distribution is taken into account directly by the method described in Ref.[2].

**5.d. How are ejectile binding energies handled?**

Using corrected Cameron formula.

**5.e. Is any nucleon-cluster scattering considered?**

No.

**5.f. Are ejectiles subject to surface refraction/reflection angular distributions?**

**5.g. What channels other than neutron and proton are treated e.g. alpha, deuterons, tritons, pi, K, p, etc.?**

Pions and muons are considered for cascade stage, deuterons, tritons, He-3, alpha and more heavy fragments are treated for equilibrium stage of reaction.

**5.h. How is the transition made to the next phase of the calculation?**

**5.i. What criteria for p-h excitation? is the next phase precompound or compound'?**

The next phase is compound.

**6. If there is a precompound phase, describe the PE model used, parameters, i.e. partial state densities, transition rates?**

No PE phase.

**7. What physics are used for the final de-excitation stage ?**

Level density are calculated using Fermi gas model.  
The inverse cross-sections are calculated via the "sharp cut-off" model.

**8. Is there any limit as to the number of nucleons from target for which yields may be calculated?**

No.

**9. Any other comments on aspects not covered in the above questions?**

**10. References to the literature or reports discussing these codes as implemented'?**

- [1] V.S.Barashenkov et al., Preprint of JINR, R2-85-173, 1985.
- [2] V.S.Barashenkov et al., Nucl. Phys. A338 (1980) 413.
- [3] V.S.Barashenkov, Preprint of JINR, R2-89-770, 1989.

**Code Information Questionnaire****I. General Questions:****1. Name of the code**

DISCA

**2. First name of the participant**

Yu.N.Shubin, A.Yu.Konobeyev, V.P.Lunev

**3. Responsible author of the code**

A.Yu.Konobeyev, V.P.Lunev, Yu.N.Shubin

**4. Reference for the code**

Report IPPE, 1996, is under preparation

**5. Is a manual available?**

A manual is given in comments to the code listing

**6. What nuclear reaction models are contained?**

Modified intranuclear cascade model, evaporation model

**7. Range of targets allowed**~  $10 < A < 209$ **8. Range of projectiles allowed**

Neutrons, protons, alpha-particles

**9. Incident energy regime permitted**

&lt; 1 GeV

**VI.2. Specific Questions:****1. How are reaction cross-sections generated in the entrance channel?**

Reaction cross-sections are calculated. Total cross-sections are obtained via relation  $\pi(R+l)^{1/2}$ , where R is the radius of the outer zone, l is the wavelength of the incident particle.

**2. What nuclear density distribution is used and how do these enter the calculation?**

Ten concentric nucleus zone with the constant density are considered. The radius of the outer zone is estimated under condition that the nuclear density is equal 0.01 x density in the nucleus center.

**3. Is the Fermi energy calculated in a local density approximation?**

Yes.

**4. What nuclear radius parameterization is used'?**

$R_0 = 1.2 \text{ fm}$ .

**5. For INC models:**

**5.a. What nucleon nucleon cross-sections are used? Are energy and isospin dependent?**

Nucleon-nucleon cross-sections from Refs.[1,2] are used in calculations. Cross-sections are energy and isospin dependent.

**5.b. How is Pauli exclusion handled in the INC?**

It is described in Ref.[3].

**5.c. How are nuclear density effects treated?**

See Q.1,Q.2

**5.d. How are ejectile binding energies handled?**

Using experimental nuclide masses and the Myers-Swiatecki formula.

**5.e. Is any nucleon-cluster scattering considered?**

Yes, the nucleon-alpha interaction is simulated. Also quasi pick-up model is used to describe alpha-emission.

**5.f. Are ejectiles subject to surface refraction/reflection angular distributions?**

Yes, both effects are treated.

**5.g. What channels other than neutron and proton are treated e.g. alpha, deuterons, tritons, pi, K, p, etc.?**

On the cascade reaction stage: alpha; on the evaporation stage: deuteron, triton, He-3, alpha.

**5.h. How is the transition made to the next phase of the calculation?**

No specific "cut-off" energy is considered.

**5.i. What criteria for p-h excitation? is the next phase precompound or compound'?**

The next phase is compound.

**6. If there is a precompound phase, describe the PE model used, parameters, i.e. partial state densities, transition rates?**

No PE phase. See Q9.

**7. What physics are used for the final de-excitation stage ?**

Level density are calculated using Fermi gas model. At the low excitation energies the "constant temperature" model is adopted. The inverse cross-sections are calculated via the optical model.

**8. Is there any limit as to the number of nucleons from target for which yields may be calculated?**

No.

**9. Any other comments on aspects not covered in the above questions?**

The preequilibrium phase described by PE models is not considered.

The reason is the inclusion in the INC algorithm of new principle:

restriction on the orbital momenta of interacting nucleons (see Ref.[4]). It compensates the deficiencies of the usual INC model and allows, as shown in Ref.[4], use the model to predict angular and energy distributions of secondary particles in the whole energy range where preequilibrium models are applicable.

**10. References to the literature or reports discussing these codes as implemented'?**

See e.g. Refs.[4-7].

[1] K.Chen et al., Phys. Rev. 166 (1968) 949.

[2] H.W.Bertini, Report ORNL-3383, 1963; ORNL-3786, 1966.

[3] V.S.Barashenkov, V.D.Tonejev, Interaction of High Energy Particles and Atomic Nuclei with Nuclei (Vzaimodeystviya Vysokoenergeticheskikh Chastits i Atomnykh Yader s Yadrarni, Moscow, 1972) [Engl. transl.: FTD-ID (RS) T-1069-77, July 1977]

[4] Yu.N.Shubin, V.P.Lunev, A.Yu.Konobeyev, Yu.A.Korovin, Proc. Spec. Meet. on Intermediate Energy Nuclear Data: Models and Codes, Issy-Les-Moulineaux, France, 30 May-1 June 1994, OECD/OCDE, Paris, p.35.

[5] A.Yu.Konobeyev, Yu.A.Korovin, Nucl. Instr. Meth., B82 (1993) 103.

[6] V.V.Artisyuk, A.Yu.Konobeyev, Yu.A.Korovin, Kerntechnik, 58 (1993) 174.

[7] A.Yu.Konobeyev, Yu.A.Korovin, J. Nucl. Mat., 195 (1992) 286; 186 (1992) 117.

**Code Information Questionnaire****I. General Questions:****1. Name of the code**

ALICE 92

**2. Name of the participant**

M. Blann

**3. Responsible author of the code**

M. Blann

**4. Reference of the code**

UCRL-JC-109052, Lawrence Livermore National Laboratory report, November 1991.

**5. Is a manual available?**

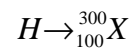
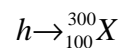
Yes

**6. What nuclear reaction models are contained?**

Precompound decay  
 hybrid  
 angular distributions from N-N scattering  
 angular distributions from systematics

Evaporation  
 Weisskopf-Ewing

Fission model  
 Bohr-Wheeler, options for fission barriers

**7. Range of targets allowed****8. Range of projectiles allowed****9. Incident energy regime permitted**

0 - 1000 MeV  
 (300 MeV excitation maximum)

**II. Specific Questions:****1. How are reaction cross-sections generated in the entrance channel?**Optical model for  $Z \leq 2$ , parabolic model  $Z > 2$ .

**2. What nuclear density distribution is used, and how does it enter the calculation?**

Fermi density distribution for precompound decay uses Thomas-Fermi local density approximation.

**3. Is the Fermi energy calculated in a local density approximation?**

Yes, in geometry dependent hybrid model.

**4. What nuclear radius parameterization is used?**

Fermi density distribution with parameters based on Myers droplet model.  
Central density radius =  $1.18A^{1/3} (1 - (1/1.18A^{1/3})^2)$  range parameter  $Z = 0.55$ .  
This is used for precompound local density calculation.

For reaction, inverse cross sections, optical parameters are used as given in Phys. Rev. C28 (1983) 1975.

**5. For INC models**

**6. If there is a precompound phase, describe the PE model used, parameters, i.e., partial state densities, transition rates?**

Precompound decay model used: hybrid model with parameters given in Phys. Rev. C28 (1983) 1475. Hybrid model is described in Phys. Rev. Lett. 27 (1971) 337 partial state densities are Ericson-Williams exciton densities; transition rates from Pauli corrected n-n scattering or from imaginary optical potential. No adjustable parameters. Multiple P.E. decay is treated.  
no clusters treated in PE phase  
non-relativistic kinematics/phase space  
Angular distributions may be calculated from N-N scattering kinematics or using Kallbach systematics; inverse cross sections may be selected either from optical model or from classical sharp cutoff model.

**Are clusters multiple PE decay, relativistic kinematics used?**

Multiple PE decay

**How are angular distributions computed?**

N-N scattering kinematics as per Goldberger, or systematics. Latter option, due to Kalbach, used in this submission

**Source of inverse cross-sections?**

See 4.

**7. What physics are used for the final de-excitation state: evaporation model, Fermi breakup?**

Weisskopf-Ewing model with n, p, d, a in exit channel is used in standard version of ALICE. Other versions allow 23 ejectiles per nuclide. A fermi gas level density is used with default  $a = A/9$ . Inverse cross sections are generated from the nuclear optical model. Parameters for optical model are given in Phys. Rev. C28 (1983) 1475. Excitations up to 300 MeV in standard release. Exclusive product yields are produced, but emission spectra are inclusive.

**Describe parameters used: level densities, inverse cross-sections or transmission coefficient, choice of optical model parameters if relevant (or reference to source), range of excitations allowed, inclusive or exclusive results?**

**8. Is there any limit as to the number of nucleons from target for which yields may be calculated?**

Yields may be calculated for neutron numbers up to 22 fewer and proton numbers up to 9 fewer than the CN.

**9. Any other comments on aspects not considered in the above questions?**

The precompound calculation is invalid above incident energies around 270 MeV/nucleon since no pion physics is entered into N-N kinematics, and Ericson partial state densities should not work in this case.

**10. References to the literature or reports discussing these codes as implemented?**

See reference in question #6 and LLNL Report UCRL-JC-109052, November 21, 1991.



**Code Information Questionnaire****I. General Questions:****1. Name of the code**

ALICE-IPPE

**2. Name of the participant**

Yu. N. Shubin, A.Yu. Konobeyev, V. P. Lunev

**3. Responsible author of the code**

M.Blann, V. P. Lunev, A.Yu. Konobeyev, Yu. N. Shubin

**4. Reference of the code**

Reports UCID-19614, UCID-20169,

IAEA Report INDC(CCP)-385, Vienna 1995

**5. Is a manual available?**

The manual is under preparation.

**6. What nuclear reaction models are contained?**

The precompound decay:

Hybrid and geometry dependent form with parameters given in Phys.Rev. C28 (1983)1475.

Hybrid model is described in Phys.Rev.Lett. 27(1971)337.

Partial level densities are Williams exciton densities.

Transition rates from Pauli corrected N-N scattering or from imaginary optical potentials.

Preequilibrium emission of clusters unifying knock-out and pick-up coalescence models.

Angular distribution may be calculated from Kalbach systematics or from N-N scattering kinematics.

Nonrelativistic kinematics.

The evaporation model:

Weisskopf-Ewing.

Fission model:

Bohr-Wheeler, options for fission barriers.

**7. Range of targets allowed**Approximately  $A > 20$ .**8. Range of projectiles allowed**

Unrestricted

**9. Incident energy regime permitted**

0 - 300 MeV.

## VI.2. Specific Questions:

### 1. How are reaction cross-sections generated in the entrance channel?

Reaction cross section for neutron, proton, deuteron and alpha particles from optical model or from sharp cutoff systematic Phys. Rev. **C21** (1980) 1770. For heavier charged particle, optical model with parabolic potential is used.

### 2. What nuclear density distributions are used, and how does it enter the calculation?

Density distribution in Fermi form.

### 3. Is the Fermi energy calculated in a local density approximation?

The Fermi energy calculated in a local density approximation in geometry dependent hybrid model.

### 4. What nuclear radius parametrization is used?

Fermi density distribution with parameters based on Myers droplet model

Fermi density distribution for GDH model:

$$d(Rl) = ds / (1 + \exp((Rl - C) / 0.55)) \quad (1)$$

radius for partial wave L:  $Rl = \lambda(L + 1/2)$ ,  $ds$  - saturation density for nuclear matter.

Charge radius  $C = 1.18 A^{1/3} (1 - 1 / (1.18 A^{1/3})^2) + \lambda$  fm.

For hybrid model, nuclear density is obtained by integrating (1) from 0 to  $C + 2.75$  fm

### 5. For INC models

### 6. If there is a precompound phase, describe the PE model used, parameters, i.e., partial state densities, transition rates?

Nonrelativistic kinematics.

The hybrid or geometry dependent hybrid model is used.

For partial state density, William's state density is adopted with the equidistant model parameter  $A/13$ .

Angular distributions from Kalbach systematic, Phys. Rev. **C37**, (1988) 2350 or from N-N scattering kinematics.

Nonrelativistic kinematics.

### 7. What physics are used for the final de-excitation state: evaporation model, Fermi breakup?

For final de-excitation stage evaporation model is used. Weisskopf-Ewing model with n, p, d, alpha,  $^3\text{He}$ ,  $^3\text{H}$  and gamma in exit channel is used in the code. Level density of unified superfluid model with vibrational and rotational phenomenological enhancement and damping of the collective effects is used.

Inverse reaction cross sections are generated from the nuclear optical model, sharp cutoff approximation and parabolic approximation. Parameters for optical model given in Phys. Rev. **C28**, (1983) 1475.

Free N-N cross section from new Kalbach systematic, Phys. Rev. **C41** (1990) 1651.

### 8. Is there any limit as to number of nucleons from target for which yields may be calculated?

Yields may be calculated for neutron number 22 fewer and proton numbers 9 fewer than CN.

### 9. Any others comments

The precompound calculation is invalid above incident energies around 270 MeV since no pion physics is entered into N-N kinematics.

**10. References to the literature or reports discussing these code.**

Main description of the code in:

Reports UCID-19614, UCID-20169

Main improvements of these code discussed in:

Izv.Acad.Nauk Ser. Phys. 49 (1985) 962.

Report IAEA INDC(CCP)-385, Vienna 1995

Acta Physica Slovaca 45 (1995) 705-716

**Code Information Questionnaire****I. General Questions****1. Name of the code**

AREL

**2. First name of the participant**

M. Gloris

**3. Responsible author of the code**

M. Blann

**4. Reference of the code**

LLNL report UCRL-88540/Phys. Rev. C28 (1983) 1475, however, without the relativistic extension (further references as for the widely known code ALICE).

**5. Is a manual available?**

No, but there are preceding instructions given in the code itself.

**6. What nuclear reaction models are contained?**

Precompound decay: geometry-dependent hybrid model  
Evaporation: Weisskopf-Ewing  
Fission model: Bohr-Wheeler

**7. Range of targets allowed**

No restrictions.

**8. Range of projectiles allowed**

No restrictions.

**9. Incident energy regime permitted**

Up to 900 MeV.

**II. Specific Questions****1. How are reaction cross-sections generated in the entrance channel?**

According to systematics given in S. Pearlstein, *Astrophys. J.* B46 (1989) 1049.

**2. What nuclear density distribution is used and how does these ~~use~~ the calculation?**

Fermi density distribution for precompound decay uses Thomas-Fermi local density approximation.

**3. Is the Fermi energy calculated in a local density approximation?**

Yes.

**4. What nuclear radius parametrization is used?**

Fermi density distribution with parameters based on Myers droplet model.

**5. For INC models**

Not implemented.

**6. If there is a precompound phase, describe the PE model used, parameters, i.e., partial state densities, transition rates?**

Precompound decay model is the geometry dependent hybrid model as described in references (see I.4.); partial state densities are Ericson-Williams exciton densities; transition rates from Pauli-corrected N-N scattering.

**Are clusters treated multiple PE decay, relativistic kinematics used?**

Multiple P.E. decay is treated without any clusters; relativistic kinematics/phase space.

**How are angular distributions computed?**

Via systematics expressions of Kalbach or NN scattering kinematics can be used.

**Source of inverse cross-sections?**

Optical model scaled to the Pearlstein calculated reaction cross section (see II.1.).

**7. What physics are used for the final de-excitation state?**

Weisskopf-Ewing statistics is applied in evaporation phase with n, p and  $\alpha$  in exit channel.

**Describe parameters used: level densities, inverse cross-sections or transmission coefficient, choice of optical model parameters if relevant (or reference to source), range of excitations allowed, inclusive or exclusive results?**

A fermi gas level density is used with default  $a = A/9$ ; inverse cross sections are generated from optical model (parameters are given in Phys. Rev. [C28](#) (1983) 1475) and scaled to the Pearlstein calculated reaction cross section.

**8. Is there any limit as to the number of nucleons from target for which yields may be calculated?**

Yes, yields may only be calculated for residual nuclei with neutron numbers up to 22 fewer and proton numbers up to 9 fewer than the CN.

**9. Any other comments on aspects not considered in the above questions?**

AREL is yet another version of the widely used ALICE code. It differs from these versions mainly in the relativistic kinematics/phase space and in the incident energy regime permitted.

Some efforts were undertaken to produce well shaped excitation functions which was achieved by slightly adjusting incident energies as well as using a constant energy binning of 0.5 MeV over the whole energy range.

Nevertheless, it must be emphasized that the enhancement to use incident particle energies up to 900 MeV is simply achieved by enlarging array dimensions in the code - no new physical effects as for example pion production are considered.

Above questions are mostly answered with respect to the options used in this exercise. There are a lot of possible other options (as well as other code variants are existing), however, it is not possible to combine these options with each other because this results in most cases in a crash while running the program.

**10. References to the literature or reports discussing these codes implemented?**

T. Schiek et al., Nucl. Instr. Meth. Res. (1996), in press

**Code Information Questionnaire****I. General Questions:****1. Name of the code:**

HMS-ALICE

**2. Name of the participant**

M. Blann

**3. Responsible author of the code**

M. Blann

**4. Reference of the code**

UCRL-JC-109052, Lawrence Livermore National Laboratory, November 1991, &amp; UCRL-JC-123495, February 1996

**5. Is a manual available?**

YES

**6. What nuclear reaction models are contained?**

Precompound decay  
 HMS (Hybrid Monte Carlo Simulation)  
 angular distributions from systematics  
 Evaporation  
 Weisskopf-Ewing  
 Fission Model  
 Bohr-Wheeler, options for fission barriers

**7. Range of targets allowed**

300  
 H-> X  
 110

**8. Range of projectiles allowed**

300  
 h-> X  
 110

**9. Incident energy regime permitted**

0-1000 MeV

**II. Specific Questions****1. How are reaction cross-sections generated in the entrance channel?**Optical model for  $Z.=BE2$ , parabolic model  $Z>2$ .

**2. What nuclear density distribution is used, and how does it enter the calculation?**

Fermi density distribution for precompound decay uses Thomas-Fermi local density approximation.

**3. Is the Fermi energy calculated in a local density approximation?**

Yes, in geometry dependent version of HMS; in this exercise only the result averaged over the nuclear volume is used.

**4. What nuclear radius parameterization is used?**

Fermi density distribution with parameters based on Myers droplet model.

Central density radius =  $1.18A^{1/3} (1 - (1/1.18A^{1/3})^2)$  range parameter  $Z=0.55$ .

This is used for precompound local density calculation.

For reaction, inverse sections, optional parameters are used as given in Phys. Rev. C28 (1983) 1975.

**5. For INC models**

**6. If there is a precompound phase, describe the PE model used, parameters, i.e., partial state densities, transition rates?**

Precompound decay model used: HMS model with parameters given in Phys. Rev. C28 (1983) 1475 for the Hybrid model. Partial state densities are Ericson exciton densities used only for 2 and 3 exciton cases. Transition rates from Pauli corrected n-n scattering. No adjustable parameters.

Multiple P.E. decay is treated, with no limit on number of Precompound nucleons other than that due to nature.

no clusters treated in PE phase

relativistic kinematics/phase space

Angular distributions may be calculated using Kallbach systematics; inverse cross sections may be selected either from optional model or from classical sharp cutoff model.

Are clusters multiple PE decay, relativistic kinematics used?

Multiple PE decay, no limit on number of nucleons; relativistic kinematics

How are angular distributions computed?

Kalbach systematics presently only available for HMS option used in this submission.

Source of inverse cross-sections?

See 4.

**7. What physics are used for the final de-excitation state: evaporation model, Fermi breakup?**

Weisskopf-Ewing model with n,p,d,alpha in exit channel is used in standard version of ALICE.

Other versions allow 23 ejectiles per nuclide.

A fermi gas level density is used with default  $a = A/9$   
or



the shell corrected model of Kataria and Ramamurthy may be used. The latter was used in V and Co target results of this work. The Gilbert-Cameron model is also an option in all recent ALICE codes.

Inverse cross sections are generated from the nuclear optical model.

Parameters for optical model are given in Phys.Rev.C28 (1983) 1475.

Excitations up to 600 MeV in HMS- Alice may be treated.

Describe parameters used: level densities, inverse cross-sections or transmission coefficient, choice of optical model parameters if relevant (or reference to source), range of excitations allowed, inclusive or exclusive results?

**8. Is there any limit as to the number of nucleons from target for which yields may be calculated?**

Yields may be calculated for neutron numbers up to 22 fewer and proton numbers up to 9 fewer than the CN.

**9. Any other comments on aspects not considered in the above questions?**

The precompound calculation starts to become questionable above around 400 MeV/nucleon since no pion physics is entered into N-N kinematics. Later versions should include pion physics, and be applicable to 1 GeV

**10. References to the literature or reports discussing these codes as implemented?**

See reference in question #6 and LLNL Report UCRL-JC-109052, November 21, 1991, also LLNL Report UCRL-JC-123495- February, 1996.

**Code Information Questionnaire****I. General Questions:****1. Name of the code**

PEQAG2 (extended)

**2. Name of the participant**

Emil Betak

**3. Responsible author of the code**

Emil Betak

**4. Reference of the code**

- a) Betak, Report INDC(CSR)-016/LJ (IAEA Vienna 1989);
- b) Betak: Report FU SAV 89/5 (Inst. Phys. Bratislava 1989)  
(this is an update of IAEA report)

**5. Is a manual available?**

Yes

**6. What nuclear reaction models are contained?**

Precompound decay in exciton master equation

**7. Range of targets allowed**

Recommended  $A > 40$

**8. Range of projectiles allowed**

n, p, d, t, he-3, alpha, gamma, heavy ions

**9. Incident energy regime permitted**

Excitation energy of composite system  $< 500 - 800$  MeV, but recommended  $150 - 200$  MeV.

**II. Specific Questions:****1. How are reaction cross-sections generated in the entrance channel?**

Reaction cross sections in the entrance channel may be supplied on the input. Default (which has been used for this intercomparison) is the formula by Chatterjee, Gupta, and Murthy (set of papers, 1980-1981).

**2. What nuclear density distribution is used, and how does it enter the calculation?**

No dependence on nuclear matter density.

**3. Is the Fermi energy calculated in a local density approximation?**

Fermi energy approximated by fixed value of 40 MeV.

**4. What nuclear radius parameterization is used?**

Nuclear radius enters just the reaction c.s. (see item 1).

**5. For INC models**

Not INC model.

**6. If there is a precompound phase, describe the PE model used, parameters, i.e., partial state densities, transition rates?**

Precompound phase throughout all the reaction chain.

Equidistant-spacing model (Williams-like formula) with correction to finite depth of nuclear potential.

$g = A/13$ , no pairing.

Using  $|M|^2$ , parameterized in its form which depends on the excitation energy per exciton (see Kalbach).

Used  $K' = 100 \text{ MeV}^3$ .

**Are clusters multiple PE decay, relativistic kinematics used?**

No clusters, only non-relativistic kinematics.

**How are angular distributions computed?**

No angular distributions.

**Source of inverse cross-sections?**

"Approximated using closed formulae according to A. Chatterjee et al., Pramana 16 (1981), 391; Nucl. Phys. Solid State Phys. Symp., Delhi 1980; private comm. (1981)."

**7. What physics are used for the final de-excitation state: evaporation model, Fermi breakup?**

De-excitation stage done fully in precompound manner (exciton master equations, see above).

**Describe parameters used: level densities, inverse cross-sections or transmission coefficient, choice of optical model parameters if relevant (or reference to source), range of excitations allowed, inclusive or exclusive results?**

Results can be obtained both inclusive and exclusive. In the present intercomparison, only the inclusive spectra are sent (the exclusive ones may be supplied in a short time).

**8. Is there any limit as to the number of nucleons from target for which yields may be calculated?**

Dimensions of arrays set to 6 subsequent nucleons (which can be interspaced by gammas in arbitrary amount and order).

**9. Any other comments on aspects not considered in the above questions?**

I do not think so.

**10. References to the literature or reports discussing these codes as implemented?**

a) Previous intercomparisons.

b) Gruppelaar et al.: Riv. N. Cim. 9 (1986) No. 7.

c)

Betak: Varenna lectures 1988 and 1991;

Betak, Dobes: Phys. Lett. B30 (1983) 350;

Cvelbar et al.: J. Phys. G7 (1991) 113;

Betak et al.: Phys. Rev. G6 (1992) 945.

**Code Information Questionnaire****I. General Questions:****1. Name of the code**

FKK-GNASH

**2. Name of the participant**

M.B. Chadwick and P.G Young

**3. Responsible author of the code**

Mark Chadwick - pre-equilibrium part  
Philip Young - Hauser Feshbach part

**4. Reference of the code**

M. B. Chadwick and P. G. Young, LA-UR-93-104

**5. Is a manual available?**

Yes. Full details of the present calculations, as well as a description of the FKK codes which link into GNASH are given in "FKK-GNASH Calculations of (p,xn) and (p,xp) Reactions on  $^{90}\text{Zr}$  and  $^{208}\text{Pb}$  for NEA Code Intercomparison", M. B. Chadwick and P. G. Young, Los Alamos Report LA-UR-93-104 (1993).

A description of the GNASH code is presented in "Comprehensive Nuclear Model Calculations: Introduction to the Theory and Use of the GNASH Code", P. G. Young, E. D. Arthur, and M. B. Chadwick, Los Alamos Report LA-12343-MS (1992).

**6. What nuclear reaction models are contained?**

Precompound decay: Quantum mechanical multi-step (FKK)

Evaporation: Hauser Feshbach

**7. Range of targets allowed**

Approximately  $A > 20$

**8. Range of projectiles allowed**

Neutrons or protons, so far

**9. Incident energy regime permitted**

Approximately  $E < 200$  MeV

**II. Specific Questions:****1. How are reaction cross-sections generated in the entrance channel?**

Using a spherical or deformed optical potential, with codes ECIS or STAT89.

**2. What nuclear density distribution is used, and how does it enter the calculation?**

Does not explicitly enter the calculation, but it does implicitly due to its dependence on nucleon bound wave functions that are used.

**3. Is the Fermi energy calculated in a local density approximation?**

N/A

**4. What nuclear radius parameterization is used?**

$$r = 1.2 A^{1/3} \text{ fm}$$

**5. For INC models**

**6. If there is a precompound phase, describe the PE model used, parameters, i.e., partial state densities, transition rates?**

The quantum mechanical FKK theory has been used to calculate the emission of a preequilibrium neutron or proton. Two distinct mechanisms can take place: Multistep Compound emission (MSC), in which the preequilibrium cascade passes through bound states until emission occurs; and Multistep Direct emission (MSD), in which at least one of the particles remains in the continuum during the cascade. MSC emission can only occur for incident energies below about 50 MeV, and is usually not important above 30 MeV. Therefore, in the present calculations we have only included MSC in the 25 MeV incident energy cases. MSD is important at all the energies considered. The phenomenon of crossover transitions from the MSD to MSC preequilibrium chain is included in the calculations.

Partial level densities for the MSD calculations were taken from the Williams formula with finite hole depth restrictions,

$$B(p, h, E) = \frac{g^n}{p! h! (n-1)!} \sum_{j=0}^h (-1)^j \binom{h}{j} (E - \Delta - A_{ph} - j \epsilon_F)^{n-1} \times (E - \Delta - A_{ph} - j \epsilon_F)$$

(1)

where  $g = A/14$ ,  $\Delta$  is the pairing energy of Dilg and  $A_{ph} = (p^2 + h^2 + p - 3h)/4g$  is the Pauli-blocking factor.  $B$  is the average neutron and proton binding energy, and  $\epsilon_F$  the Fermi-energy which we take to be 35 MeV. The theta-function is unity if its argument is positive, and zero otherwise. The spin distribution of p-h states is taken to be a Gaussian with spin cut-off  $\sigma^2 = 0.24nA^{2/3}$ . In the MSC calculations, a Williams-type formula similar to the above was used, but with the further restriction that the particle excitations remain bound.

In the FKK formalism the total MSD cross section is given as a sum of the various MSD preequilibrium stage contributions, and the cross section for each of the multistep processes is given in terms of a convolution of 1-step processes. Thus, MSD 1-step cross sections are required at both the incident energy of interest, and at all lower incident energies. In practice, this is done by calculating 1-step cross sections at five lower incident energies in addition to the incident energy of interest, and interpolating the results for other incident energies. We calculate the form factor for the various transitions with DWUCK4 using a Yukawa potential of range 1fm, and strength  $V_0$ , for 1p1h excitations. With a CRAY computer we have no difficulty in averaging a large sample of microscopic 1p1h DWUCK4 cross sections (typically, for each energy calculated, we average twenty-seven microscopic DWBA cross sections). When calculating the form factors, unbound-state wavefunctions were obtained from optical-potential scattering states, and bound-

states from a real Wood-Saxon potential well with radius parameter 1.2 fm and diffuseness 0.6 fm. We apply a Gaussian smoothing to our calculated MSD cross sections of width 2 MeV, to remove artificial fluctuations which would not arise if we used deformed Nilsson single-particle states. We have found an approximate energy dependence of the residual interaction strength  $V_0^2 \mu / E_{\text{inc}}$  and therefore incorporate this energy dependence into our multistep calculations.  $V_0$  is the only free parameter entering the MSD calculations, and is extracted in the following way:

1. For the 80 and 160 MeV incident energies, the first-stage MSD preequilibrium processes were assumed to exhaust the reaction cross section, allowing  $V_0$  to be uniquely determined. It is important to note that we do not vary  $V_0$  so that the MSD reactions account for all the observed preequilibrium emission, as has been done in all previous MSD analyses by other authors. We find that for these high incident energies, such a procedure leads to a violation of unitarity, since the integrated neutron and proton MSD then exceeds the reaction cross section. Instead, we find that multiple preequilibrium processes (described below) account for much of the observed high-emission energy data.
2. For the 25 and 45 MeV incident energies, the above procedure cannot be used since preequilibrium processes no longer account for the whole reaction cross section, and primary Hauser-Feshbach emissions important. However, multiple preequilibrium effects are not very important at these low energies, and so  $V_0$  can be obtained by matching the MSD emission to the difference between the high energy differential data, and the calculated MSD.

#### **Are clusters multiple PE decay, relativistic kinematics used?**

While the FKK theory was used to describe preequilibrium emission of a first emitted neutron or proton, further preequilibrium emissions ("multiple preequilibrium") was included using an exciton model.

#### **How are angular distributions computed?**

The angular distributions are obtained theoretically from the FKK and Hauser-Feshbach theories. Since the preequilibrium multiple emission cross section was calculated from the exciton model, we assumed that its angular distribution is equal to that of the MSD 2-step.

#### **Source of inverse cross-sections?**

### **7. What physics is used for the final de-excitation state: evaporation model, Fermi breakup?**

The full angular-momentum dependent version of the Hauser-Feshbach model in the GNASH code is incorporated into FKK-GNASH. Before performing the analysis, trial calculations were performed with 160 MeV protons incident on  $^{90}\text{Zr}$  and  $^{208}\text{Pb}$  to determine the reaction sequences that make significant (greater than  $\sim 1$  mb) contributions to the proton and neutron emission spectra. The decay sequence used in the p- $^{90}\text{Zr}$  calculation includes neutron, proton, and g-ray decay for Nb isotopes from  $^{91}\text{Nb}$  through  $^{85}\text{Nb}$ , for Zr isotopes from  $^{90}\text{Zr}$  through  $^{85}\text{Zr}$ , for Y isotopes from  $^{89}\text{Y}$  through  $^{83}\text{Y}$ , for Sr isotopes from  $^{88}\text{Sr}$  through  $^{82}\text{Sr}$ , and for Rb isotopes from  $^{87}\text{Rb}$  through  $^{82}\text{Rb}$ . Additionally, alpha-particle emission was included for the primary channel. In the case of the p- $^{208}\text{Pb}$  calculation, neutron and g-ray decay are included for Bi isotopes from  $^{209}\text{Bi}$  through  $^{192}\text{Bi}$  and for Pb isotopes from  $^{208}\text{Pb}$  through  $^{196}\text{Pb}$ . Additionally, proton and deuteron emission are allowed for the primary channel, and proton emission is permitted for the  $^{208}\text{Bi}$  and  $^{208}\text{Pb}$  compound nuclei. No other reactions produce significant contributions to the neutron or proton emission spectra.

For the p- $^{90}\text{Zr}$  calculations, the standard Gilbert and Cameron level density model was used, together with default Gilbert and Cameron values for the level density parameters. Level densities for the p- $^{208}\text{Pb}$  calculations were obtained from the Ignatyuk. For both the  $^{90}\text{Zr}$  and  $^{208}\text{Pb}$  calculations, estimates of gamma-ray competition were made using gamma-ray strength functions from the model of Kopecky and Uhl. Although GNASH includes a double-humped

fission barrier model, competition from fission was not included in the p-<sup>208</sup>Pb analysis because it is estimated to contribute less than 5% of the reaction cross section at the highest energy considered.

**Describe parameters used: level densities, inverse cross-sections or transmission coefficient, choice of optical model parameters if relevant (or reference to source), range of excitations allowed, inclusive or exclusive results?**

- 8. Is there any limit as to the number of nucleons from target for which yields may be calculated?**

No

- 9. Any other comments on aspects not covered in the above questions?**

- 10. References to the literature or reports discussing these codes as implemented?**

See references in answer to Q.5. In addition, see "Feshbach-Kerman-Koonin Analysis of <sup>93</sup>Nb Reactions: P-Q Transitions and Reduced Importance of Multistep Compound Emission", M. B. Chadwick and P. G. Young, Phys. Rev. C47, 2255 (1993).



**Code Information Questionnaire****I. General Questions:****1. Name of the code:**

MINGUS95

**2. Name of the first participant:**

A.J. Koning

**3. Responsible author of the code:**

A.J. Koning

**4. Reference for the code:**

- A.J. Koning, O. Bersillon and J.-P. Delaroche, "Quantum-mechanical direct, pre-equilibrium and equilibrium spectra up to 200 MeV", proceedings of the International Conference on Nuclear Data for Science and Technology, 1072-1074, ed. J.K. Dickens, May 9-13 1994, Gatlinburg, Tennessee USA

- A.J. Koning, O. Bersillon and J.-P. Delaroche, "Nuclear model calculations below 200 MeV and evaluation prospects", proceedings of the NEA Specialist Meeting on Intermediate Energy Nuclear Data: Models and Codes, 87-105, May 30-June 1 1994, Issy-les-Moulineaux, France

- A.J. Koning and H. Gruppelaar, "Nuclear Data Hybrid Nuclear Systems", contribution to the International Conference GLOBAL '95 - Evaluation of Emerging Nuclear Fuel Cycle System, 855-862, Versailles, France, September 11-14 1995.

**5. Is a manual available?**

No

**6. What nuclear models are contained?**

Direct reactions + Quantum-mechanical multi-step + Hauser-Feshbach

**7. Range of targets allowed:**

A= 12-260

**8. Range of projectiles allowed:**

n, p, d, t, h, a

**9. Incident energy range permitted:**

5 - 200 MeV

**II. Specific questions:****1. How are reaction cross-sections generated in the entrance channel?**

They are calculated with an optical model using the code ECIS95.

2. **What nuclear density distribution is used, and how does it enter the calculation?**

3. **Is the Fermi energy calculated in a local density approximation?**

4. **What nuclear radius parameterization is used?**

5. **For INC models**

6. **Precompound phase?**

The precompound phase of the reaction is calculated with the Feshbach-Kerman-Koonin multi-step direct and multi-step compound models. For the particle-hole state density, the Betak-Dobes formula is used (i.e. the Williams formula including finite depth of the hole). The multi-step direct model involves microscopic DWBA cross sections. Contributions from 5 steps are included. The multiple MSD method of Chadwick et al. is used for multiple pre-equilibrium emission. Angular distributions follow directly from our quantum-mechanical approach.

7. **Evaporation phase?**

The first evaporation stage is treated with the Hauser-Feshbach model and the latter stages with the Weisskopf-Ewing model. The transmission coefficients and inverse reaction cross sections are calculated with the optical model using ECIS95.

8. **Is there any limit as to the number of nucleons from target for which yields may be calculated?**

No

9. **Other comments?**

Our contribution is limited to  $^{59}\text{Co}$ ,  $\text{Fe}(\text{nat})$ ,  $\text{Zr}(\text{nat})$  and  $^{197}\text{Au}$  and to energies below 200 MeV.

Optical models used:

$^{59}\text{Co}$ ,  $\text{Zr}$  and  $^{197}\text{Au}$ ::  
neutrons - Walter-Guss: 0 - 90 MeV; Madland: 90 -200 MeV  
protons - Becchetti-Greenlees: 0 - 90 MeV; Madland: 50 -200 MeV  
deuterons- Lohr-Haeberli: 0 -200 MeV  
tritons - Becchetti-Greenlees: 0 -200 MeV  
helium-3 - Becchetti-Greenlees: 0 -200 MeV  
alpha's - MacFarlane: 0 -200 MeV

Fe:  
neutrons - Pedroni et al.: 0 -120 MeV; Madland: 120-200 MeV  
protons - Vuillier-Delaroche : 0 -200 MeV  
deuterons- Lohr-Haeberli: 0 -200 MeV  
tritons - Becchetti-Greenlees: 0 -200 MeV  
helium-3 - Becchetti-Greenlees: 0 -200 MeV  
alpha's - MacFarlane: 0-200 MeV

Furthermore:  
 $^{90}\text{Zr}$  - direct reaction cross sections for 24 discrete levels included  
 $^{56}\text{Fe}$  - direct reaction cross sections for 23 discrete levels included

10. **References?**

See General question no. 4

**Code Information Questionnaire****I. General Questions:****1. Name of the code**

QMDRELP + SDMRELP

**2. Name of the participant**

S. Chiba and O. Iwamoto

**3. Responsible author of the code**

K. Niita et al.

**4. Reference of the code**

Phys. Rev. C52 (1995) 2620

**5. Is a manual available?**

No

**6. What nuclear reaction models are contained?**

Quantum Molecular Dynamics + Weisskopf-Ewing + Nakahara's fission model

**7. Range of targets allowed**

no limitation

**8. Range of projectiles allowed**

no limitation

**9. Incident energy regime permitted** $\leq 5$  GeV**II. Specific Questions:****1. How are reaction cross-sections generated in the entrance channel?**

based on the impact-parameter dependent transparency

**2. What nuclear density distribution is used, and how does it enter the calculation?****3. Is the Fermi energy calculated in a local density approximation?****4. What nuclear radius parameterization is used?**

All three items (2 - 4) are determined in a self-consistent manner by the Newtonian equation of motion (no antisymmetrization is carried out)

**5. For INC models**

**5.a. What nucleon nucleon cross-sections are used? Are energy and isospin dependent?**

Cugnon type parametrization + resonance model (see reference)

**5.b. How is Pauli exclusion handled in the INC?**

as the VUU theory, i.e., based on the occupation probability of the r- and p-phase space.

**5.c. How are nuclear density effects treated?**

There is no density dependence in the N-N cross sections.

**5.d. How are ejectile binding energies handled?**

Based on the Newtonian equation of motion in the self-consistent mean field.

**5.e. Is any nucleon-cluster scattering considered?**

no

**5.f. Are ejectiles subject to surface refraction/reflection angular distributions?**

yes

**5.g. What channels other than neutron and proton are treated e.g. alpha, deuterons, tritons, pi, K, p, etc.?**

pi, through delta(1232) and N\*(1440)

**5.h. How is the transition made to the next phase of the calculation?**

based on the cluster-chaining method

**5.i. What criteria for p-h excitation? is the next phase precompound or compound'?**

compound

**6. If there is a precompound phase, describe the PE model used, parameters, i.e., partial state densities, transition rates?**

**Are clusters multiple PE decay, relativistic kinematics used?**

**How are angular distributions computed?**

**Source of inverse cross-sections?**

no precompound phase is included explicitly

**7. What physics are used for the final de-excitation state: evaporation model, Fermi breakup?**

**Describe parameters used: level densities, inverse cross-sections or transmission coefficient, choice of optical model parameters if relevant (or reference to source), range of excitations allowed, inclusive or exclusive results?**

Weisskopf-Ewing evaporation model, with a simplified inverse reaction cross section  
Level density parameter  $a=A/8$ .

**8. Is there any limit as to the number of nucleons from target for which yields may be calculated?**

no limitation

**9. Any other comments on aspects not conserved in the above questions?**

**10. References to the literature or reports discussing these codes as implemented?**

Phys. Rev. C52(1995)2800,  
Phys. Rev. C53(1996)1824,  
Phys. Rev. C54 (1996) 285,  
Phys. Rev. C, December 1996 (in press).

**Code Information Questionnaire****I. General Questions:****1. Name of the code**

SPALL (modified) / Yield

**2. Name of the participant**

R. Michel, M. Gloris

**3. Responsible author of the code**

The responsible authors for the semi-empirical model [1] used are R. Silberberg and C.H. Tsao.

Two code versions of the model were used here.

The first one is SPALL (modified). It contains the semi-empirical model of Silberberg and Tsao in its original form [1] as coded in the code SPALL by J.T. Routti and J.V. Sandberg [2]. The SPALL version [2] was modified by M. Lüpke [3] for application up to the target element barium so that SPALL (modified) considers all changes and recent developments of the semi-empirical model described in refs. [4].

The second one is a more recent version of the semi-empirical model of Silberberg and Tsao [5] in form of the YIELD code [6]. It was used for the target element gold exclusively. For the other target elements it widely gives the same results as SPALL (modified).

**4. Reference of the code**

see references below.

**5. Is a manual available?**

Descriptions of SPALL (modified) can be found in refs. [2, 3] and in the comments in the codes. All modifications to SPALL are documented in the code.

The YIELD code is a set of FORTRAN subroutines which contains a description how to call and to use it. For details on the recent developments one has to read ref. [5].

**6. What nuclear reaction models are contained?**

semi-empirical model of spallation and fragmentation

**7. Range of targets allowed**

no restrictions

**8, 9 Projectiles and energy regime**

protons with energies greater than 100 MeV

**II. Specific Questions:****1. How are reaction cross-sections generated in the entrance channel?**

does not apply

2. **What nuclear density distribution is used, and how does it enter the calculation?**

does not apply

3. **Is the Fermi energy calculated in a local density approximation?**

does not apply

4. **What nuclear radius parameterization is used?** does not apply

5. **For INC models**

6. **If there is a precompound phase, describe the PE model used, parameters, i.e., partial state densities, transition rates?** does not apply

**Are clusters multiple PE decay, relativistic kinematics used?** does not apply

**How are angular distributions computed?** does not apply

**Source of inverse cross-sections?** does not apply

7. **What physics are used for the final de-excitation state: evaporation model?** does not apply

**Describe parameters used: level densities, inverse cross-sections or transmission coefficient, choice of optical model parameters if relevant (or reference to source), range of excitations allowed, inclusive or exclusive results?** does not apply

8. **Is there any limit as to the number of nucleons from target for which yields may be calculated?**

residual nuclides  $Z \geq 3$  can be calculated

9. **Any other comments on aspects not covered in the above questions?**

The semi-empirical model of Silberberg and Tsao [1,3] was developed from the initial approach for spallation reactions by Rudstam [7] by improving the coverage of further reaction modes relevant at medium energies. Several semi-empirical models or formulae were developed [1,3,7,8,9]. Common to these approaches is that excitation functions are parameterized considering the assumed or observed dependences of the cross sections on particle energy, target mass and atomic number and product mass and atomic numbers. The partially large numbers of parameters are determined by fitting methods from existing experimental cross sections. Given the large experimental uncertainties and discrepancies in the early measurements, problems with predictions of cross sections by semi-empirical formulas not necessarily reflect problems of the models but rather those of the underlying experimental data bases.

The most recent version of the Silberberg and Tsao semi-empirical model, the YIELD code, is a set of subroutines to calculate proton-nucleus partial cross sections for the production of residual nuclide  $Z \geq 3$  at energies greater than 100 MeV, including that of charge exchange. It is extremely simple to use by calling

CALL YIELD(IZ,IA,JZ,JA,E,Q)

where IZ and IA are the interger charge and mass of the target nucleus; JZ and JA that of the product nucleus; E the energy in MeV; and Q is the cross section value in mb. As stated by the authors [6], *the program is designed to be helpful, not as a substitute for measurement. It can be improved when more measurements are available*

10. **References to the literature or reports discussing these codes as implemented?**

[1] R. Silberberg, C.H. Tsao, *Astrophys. J.* 220 (1973) 315; *ibid* 335.

[2] J.T. Routti, J.V. Sandberg, *Comp. Phys. Comm.* 23 (1981) 411

- [3] R. Silberberg, C.H. Tsao, *Astrophys. J.* 220 (1973) 315; *ibid* 335; Silberberg, R., Tsao, C.H., Shapiro, M.M., in Shen, B.S.P., Merker, M., Editors, *Spallation Nuclear Reactions and their Applications*, D. Reidel Publ. Comp., Dordrecht, 1976, p. 49; C.H. Tsao, R. Silberberg, *Proc. 16th Intern. Cosmic Ray Conf. (Kyoto) Vol. 2 (1979) 202*; R. Silberberg, C.H. Tsao, J.R. Letaw, *Ap. J. Suppl. Ser.* 58 (1985) 873; R. Silberberg, C.H. Tsao, J.R. Letaw, *20th Int. Cosmic Ray Conf. (Moscow) Vol. 2 (1987) 133*; R. Silberberg, C.H. Tsao, J.H. Adams, J.R. Letaw, *AIP Conf. Proc.* 186, *High Energy Radiation Background in Space (Sanibel Island, Florida 1987) American Inst. Phys., New York, 1989*; and references therein.
- [4] M. Lüpke, thesis, University Hannover (1993)
- [5] L. Sihver, C.H. Tsao, R. Silberberg, T. Kanai, A.F. Barghouty, *Phys. Rev. C* 47 (1992) 1225.
- [6] C.H. Tsao (TSAO@11.94.nasa.gov), YIELD set of routines, priv. comm. to K. Sümmerer (1992).
- [7] G. Rudstam, *Z. Naturf.* 21a (1966) 1027
- [8] K. Sümmerer, W. Bröchle, D.J. Morrissey, M. Schädel, B. Szweryn, Yang Weifang, *Phys. Rev. C* 42 (1991) 2546.
- [9] W.R. Webber, J.C. Kish, D.A. Schrier, *Phys. Rev. C* 41 (1991) 530, 533, 547, 566.