

# CEM03.01 User Manual

Stepan G. Mashnik<sup>1,a</sup>, Konstantin K. Gudima<sup>2,b</sup>, Arnold J. Sierk<sup>1,c</sup>,  
Mircea I. Baznat<sup>2,d</sup>, and Nikolai V. Mokhov<sup>3,e</sup>

<sup>1</sup>*Los Alamos National Laboratory, Los Alamos, NM 87545, USA*

<sup>2</sup>*IAP, Academy of Science of Moldova, Chisinau, MD-2023, Moldova*

<sup>3</sup>*Fermi National Accelerator Laboratory, Batavia, IL 60510, USA*

## Abstract

The Fortran 77 code CEM03.01 is an extended and improved version of the earlier code CEM2k+GEM2, which is based in turn on its predecessor codes CEM2k, CEM97, CEM95, CEM92M, CEM92, and MARIAG, which implement versions of the **C**ascade-**E**xciton **M**odel (**CEM**) of nuclear reactions. CEM03.01 calculates total reaction and fission cross-sections, nuclear fissilities, excitation functions, nuclide distributions (yields) of all produced isotopes separately as well as their A- and Z-distributions, energy and angular spectra, double-differential cross-sections, mean multiplicities, *i.e.* the number of ejectiles per inelastic interaction of the projectile with the target, ejectile yields and their mean energies for  $n$ ,  $p$ ,  $d$ ,  $t$ ,  ${}^3\text{He}$ ,  ${}^4\text{He}$ ,  $\pi^+$ ,  $\pi^-$ , and  $\pi^0$ . In addition, CEM03.01 provides in its output separately the yields of **F**orward (**F**) and **B**ackward (**B**) produced isotopes, their mean kinetic energies, A- and Z-distributions of the mean emission angle, their parallel velocities, and the F/B ratio of all products in the laboratory system, distributions of the mean angle between two fission fragments, of neutron multiplicity, of the excitation energy, of momentum and angular momentum, and of mass and charge numbers of residual nuclei after the INC and preequilibrium stages of reactions, as well as for fissioning nuclei before and after fission.

CEM03.01 calculates reactions induced by nucleons, pions, bremsstrahlung and monochromatic photons on not too light targets at incident energies from  $\sim 10$  MeV ( $\sim 30$  MeV, in the case of  $\gamma + A$ ) up to several GeV. This Manual describes the basic assumptions of the improved CEM as realized in the code CEM03.01, essential technical details of the code such as the description of the input and output files, and provides the user with necessary information for practical use of and for possible modification of the CEM03.01 output, if required.

<sup>a</sup>E-mail: mashnik@lanl.gov

<sup>b</sup>E-mail: gudima@cc.acad.md

<sup>c</sup>E-mail: t2ajs@lanl.gov

<sup>d</sup>E-mail: baznat@cc.acad.md

<sup>e</sup>E-mail: mokhov@fnal.gov

# NOTICE

Copyright (2006). The Regents of the University of California. This material was produced under U.S. Government contract W-7405-ENG-36 for Los Alamos National Laboratory, which is operated by the University of California for the U.S. Department of Energy <sup>1</sup>.

The U.S. Government has rights to use, reproduce, and distribute this software. **NEITHER THE GOVERNMENT NOR THE UNIVERSITY MAKES ANY WARRANTY, EXPRESS OR IMPLIED, OR ASSUMES ANY LIABILITY FOR THE USE OF THIS SOFTWARE.** If software is modified to produce derivative works, such modified software should be clearly marked, and given a different name so as not to confuse it with the version available from LANL.

Additionally, this program is free software; you can redistribute it and/or modify it under the terms of the GNU General Public License as published by the Free Software Foundation; either version 2 of the License, or (at your option) any later version. Accordingly, this program is distributed in the hope that it will be useful, but **WITHOUT ANY WARRANTY**; without even the implied warranty of **MERCHANTABILITY** or **FITNESS FOR A PARTICULAR PURPOSE**. See the GNU General Public License for more details.

---

<sup>1</sup>The primary authors of CEM03.01 are S. G. Mashnik (LANL), K. K. Gudima (non-LANL) and A. J. Sierk (LANL). Many significant contributions were made by non-LANL authors M. I. Baznat and N. V. Mokhov.

# Contents

1. Introduction	2
2. A Brief Survey of CEM03.01 Physics	2
2.1. The INC	3
2.2. The Coalescence Model	8
2.3. Preequilibrium Reactions	9
2.4. Evaporation	14
2.5. Fission	20
2.6. The Fermi Break-Up Model	24
2.7. Total Reaction Cross Sections (Normalization)	26
3. Storage of Simulation Results	26
4. Input File	29
5. Output File	34
Acknowledgments	35
References	36
Appendix 1: Ten Examples of CEM03.01 Input Files	48
Appendix 2: Output Files for the Example Inputs	53
Appendix 3: Figures with Results from the Example Outputs	103

## 1. Introduction

The Cascade-Exciton Model (CEM) of nuclear reactions was proposed 25 years ago at the Laboratory of Theoretical Physics, Joint Institute for Nuclear Research, Dubna, USSR by Gudima, Mashnik, and Toneev [1, 2]. It is based on the Dubna IntraNuclear Cascade (INC) [3, 4] and the Modified Exciton Model (MEM) [5, 6]. It was extended to consider photonuclear reactions [7] and to describe fission cross sections using different options for nuclear masses, fission barriers, and level densities [8] and its 1995 version, CEM95, was released to the public via NEA/OECD, Paris as the code IAEA1247, and via the Radiation Safety Information Computational Center (RSICC) at Oak Ridge, USA, as the RSICC code package PSR-357 [9].

The *International Code Comparison for Intermediate Energy Nuclear Data* [10, 11] organized during 1993–1994 at NEA/OECD in Paris to address the subject of codes and models used to calculate nuclear reactions from 20 to 1600 MeV showed that CEM95 had one of the best predictive powers to describe nucleon-induced reactions at energies above about 150 MeV when compared to other models and codes available at that time.

CEM95 and/or its predecessors and its successors CEM97 [12, 13], CEM2k [14], CEM2k+GEM2 [15]–[17], CEM03 [18, 19], and the latest version, CEM03.01 [20], are used as stand-alone codes to study different nuclear reactions for applications and fundamental nuclear physics (see, *e.g.*, [21]–[27] and references therein). Parts of different versions of the CEM code are used in many other stand-alone codes, like **PICA95** [28], **PICA3** [29], **CASCADO** [30], **CAMO** [31], **MCFX** [32], **ECM** [33], and **NUCLEUS** [34]. CEM95 and some of its predecessor or successor versions are incorporated wholly, or in part in different transport codes used in many applications, like **CASCADE** [35], **MARS** [36], **MCNPX** [37], **GEANT4** [38, 39], **SHIELD** [40], **RTS&T** [41], **SONET** [42], **CALOR** [43], **HETC-3STEP** [44], **CASCADE/INPE** [45], **HADRON** [46], and others.

All CEM code versions still have some problems to be solved, just as all similar models do. Following an increased interest in intermediate-energy nuclear data in relation to such projects as the Accelerator Transmutation of nuclear Wastes (ATW), the Accelerator Production of Tritium (APT), the Spallation Neutron Source (SNS), the Rare Isotope Accelerator (RIA), Proton Radiography (PRAD) as a radiographic probe for the Advanced Hydro-test Facility, and others, for several years the US Department of Energy has supported our work on the development of an improved version of the CEM which has led to the code CEM03.01 described here.

## 2. A Brief Survey of CEM03.01 Physics

The CEM03.01 code calculates nuclear reactions induced by nucleons, pions, and photons. It assumes that the reactions occur generally in three stages. The first stage is the IntraNuclear Cascade (INC), in which primary particles can be re-scattered and produce secondary particles several times prior to absorption by, or escape from the nucleus. When the cascade stage of a reaction is completed, CEM03.01 uses the coalescence model to “create” high-energy d, t,  $^3\text{He}$ , and  $^4\text{He}$  by final-state interactions among emitted cascade nucleons, already outside of the target. The emission of the cascade particles determines the particle-hole configuration,  $Z$ ,  $A$ , and the excitation energy that is the starting point for the second, preequilibrium stage of the reaction. The subsequent relaxation of the nuclear excitation is treated in terms of an improved version of the modified exciton model of preequilibrium decay followed by the equilibrium evaporation/fission stage of the reaction. Generally, all four components may contribute

to experimentally measured particle spectra and other distributions. But if the residual nuclei after the INC have atomic numbers with  $A \leq 12$ , CEM03.01 uses the Fermi break-up model to calculate their further disintegration instead of using the preequilibrium and evaporation models. Fermi break-up is much faster to calculate and gives results very similar to the continuation of the more detailed models to much lighter nuclei. In the following we highlight the main assumptions of the models contained in CEM03.01.

## 2.1. The INC

The intranuclear cascade model in CEM03.01 is based on the standard (non-time-dependent) version of the Dubna cascade model [3, 4]. All the cascade calculations are carried out in a three-dimensional geometry. The nuclear matter density  $\rho(r)$  is described by a Fermi distribution with two parameters taken from the analysis of electron-nucleus scattering, namely

$$\rho(r) = \rho_p(r) + \rho_n(r) = \rho_0 \{1 + \exp[(r - c)/a]\} , \quad (1)$$

where  $c = 1.07A^{1/3}$  fm,  $A$  is the mass number of the target, and  $a = 0.545$  fm. For simplicity, the target nucleus is divided by concentric spheres into seven zones in which the nuclear density is considered to be constant. The energy spectrum of the target nucleons is estimated in the perfect Fermi-gas approximation with the local Fermi energy  $T_F(r) = \hbar^2[3\pi^2\rho(r)]^{2/3}/(2m_N)$ , where  $m_N$  is the nucleon mass. The influence of intranuclear nucleons on the incoming projectile is taken into account by adding to its laboratory kinetic energy an effective real potential  $V$ , as well as by considering the Pauli principle which forbids a number of intranuclear collisions and effectively increases the mean free path of cascade particles inside the target. For incident nucleons  $V \equiv V_N(r) = T_F(r) + \epsilon$ , where  $T_F(r)$  is the corresponding Fermi energy and  $\epsilon$  is the binding energy of the nucleons. For pions, CEM03.01 uses a square-well nuclear potential with the depth  $V_\pi \simeq 25$  MeV, independently of the nucleus and pion energy, as was done in the initial Dubna INC [3, 4].

The interaction of the incident particle with the nucleus is approximated as a series of successive quasifree collisions of the fast cascade particles ( $N$ ,  $\pi$ , or  $\gamma$ ) with intranuclear nucleons:

$$NN \rightarrow NN, \quad NN \rightarrow \pi NN, \quad NN \rightarrow \pi_1, \dots, \pi_i NN , \quad (2)$$

$$\pi N \rightarrow \pi N, \quad \pi N \rightarrow \pi_1, \dots, \pi_i N \quad (i \geq 2) . \quad (3)$$

In the case of pions, besides the elementary processes (3), CEM03.01 also takes into account pion absorption on nucleon pairs

$$\pi NN \rightarrow NN. \quad (4)$$

The momenta of the two nucleons participating in the absorption are chosen randomly from the Fermi distribution, and the pion energy is distributed equally between these nucleons in the center-of-mass system of the three particles participating in the absorption. The direction of motion of the resultant nucleons in this system is taken as isotropically distributed in space. The effective cross section for absorption is related (but not equal) to the experimental cross sections for pion absorption by deuterons.

In the case of photonuclear reactions, CEM03.01 follows [19] the ideas of the photonuclear version of the Dubna INC proposed initially 35 years ago by one of us (KKG) in collaboration with Iljinov and Toneev [47] to describe photonuclear reactions at energies above the Giant Dipole Resonance (GDR) region [48]. [At photon energies  $T_\gamma = 10$ –40 MeV, the de Broglie

wavelength  $\lambda/2\pi$  is of the order of 20–5 fm, greater than the average inter-nucleonic distance in the nucleus; the photons interact with the nuclear dipole resonance as a whole, thus the INC is not applicable.] Below the pion-production threshold, the Dubna INC considers absorption of photons on only “quasi-deuteron” pairs according to the Levinger model [49]:

$$\sigma_{\gamma A} = L \frac{Z(A-Z)}{A} \sigma_{\gamma d} , \quad (5)$$

where  $A$  and  $Z$  are the mass and charge numbers of the nucleus,  $L \approx 10$ , and  $\sigma_{\gamma d}$  is the total photoabsorption cross section on deuterons as defined from experimental data.

At photon energies above the pion-production threshold, the Dubna INC considers production of one or two pions; the specific mode of the reaction is chosen by the Monte-Carlo method according to the partial cross sections (defined from available experimental data):

$$\gamma + p \rightarrow p + \pi^0 , \quad (6)$$

$$\rightarrow n + \pi^+ , \quad (7)$$

$$\rightarrow p + \pi^+ + \pi^- , \quad (8)$$

$$\rightarrow p + \pi^0 + \pi^0 , \quad (9)$$

$$\rightarrow n + \pi^+ + \pi^0 . \quad (10)$$

The cross sections of  $\gamma + n$  interactions are derived from consideration of isotopic invariance, *i.e.* it is assumed that  $\sigma(\gamma + n) = \sigma(\gamma + p)$ . The Compton effect on intranuclear nucleons is neglected, as its cross section is less than  $\approx 2\%$  of other reaction modes (see, *e.g.* Fig. 6.13 in Ref. [50]). The Dubna INC does not consider processes involving production of three and more pions; this limits the model’s applicability to photon energies  $T_\gamma \lesssim 1.5$  GeV [for  $T_\gamma$  higher than the threshold for three-pion production, the sum of the cross sections (8)–(10) is assumed to be equal to the difference between the total inelastic  $\gamma + p$  cross section and the sum of the cross sections of the two-body reactions (6)–(7)].

The integral cross sections for the free  $NN$ ,  $\pi N$ , and  $\gamma N$  interactions (2)–(10) are approximated in the Dubna INC model [3] used in CEM95 and its predecessors using a special algorithm of interpolation/extrapolation through a number of picked points, mapping as well as possible the experimental data. This was done very accurately by the group of Prof. Barashenkov using all experimental data available at that time, about 35 years ago. Currently the experimental data on cross sections is much more complete than at that time; therefore we have revised the approximations of all the integral elementary cross sections used in CEM95 and its predecessors. We started by collecting all published experimental data from all available sources. Then we developed an improved, as compared with the standard Dubna INC [3], algorithm for approximation of cross sections and developed simple and fast approximations for elementary cross sections which fit very well presently available experimental data not only to 5 GeV, the upper recommended energy for the present version of the CEM, but up to 50–100 GeV and higher, depending on availability of data (see details in [12, 19]). So far, we have in CEM03.01 new approximations for 34 different types of elementary cross sections induced by nucleons, pions, and gammas. Integral cross sections for other types of interactions taken into account in CEM03.01 are calculated from isospin considerations using the former as input.

The kinematics of two-body elementary interactions and absorption of photons and pions by a pair of nucleons is completely defined by a given direction of emission of one of the secondary particles. The cosine of the angle of emission of secondary particles in the c.m. system is

calculated by the Dubna INC [3] as a function of a random number  $\xi$ , distributed uniformly in the interval  $[0,1]$  as

$$\cos \theta = 2\xi^{1/2} \left[ \sum_{n=0}^N a_n \xi^n + (1 - \sum_{n=0}^N a_n) \xi^{N+1} \right] - 1 , \quad (11)$$

where  $N = M = 3$ ,

$$a_n = \sum_{k=0}^M a_{nk} T_i^k . \quad (12)$$

The coefficients  $a_{nk}$  were fitted to the then available experimental data at a number of incident kinetic energies  $T_i$ , then interpolated and extrapolated to other energies (see details in [3, 47, 48] and references therein). The distribution of secondary particles over the azimuthal angle  $\varphi$  is assumed isotropic. For elementary interactions with more than two particles in the final state, the Dubna INC uses the statistical model to simulate the angles and energies of products (see details in [3]).

For the improved version of the INC in CEM03.01, we use currently available experimental data and recently published systematics proposed by other authors and have developed new approximations for angular and energy distributions of particles produced in nucleon-nucleon and photon-proton interactions. So, for  $pp$ ,  $np$ , and  $nn$  interactions at energies up to 2 GeV, we did not have to develop our own approximations analogous to the ones described by Eqs. (11) and (12), since reliable systematics have been developed recently by Cugnon *et al.* for the Liege INC [51], then improved still further by Duarte for the BRIC code [52]; we simply incorporate into CEM03.01 the systematics by Duarte [52]. Similarly, for  $\gamma N$  interactions, we take advantage of the event generators for  $\gamma p$  and  $\gamma n$  reactions from the Moscow INC [53] kindly sent us by Dr. Igor Pshenichnov. In CEM03.01, we use part of a data file with smooth approximations through presently available experimental data, developed for the Moscow INC [53] and have ourselves developed a simple and fast algorithm to simulate unambiguously  $d\sigma/d\Omega$  and to choose the corresponding value of  $\Theta$  for any  $E_\gamma$ , using a single random number  $\xi$  uniformly distributed in the interval  $[0,1]$  (see details in [19]).

The analysis of experimental data has shown that the channel (8) of two-pion photoproduction proceeds mainly through the decay of the  $\Delta^{++}$  isobar listed in the last Review of Particle Physics by the Particle Data Group as having the mass  $M = 1232$  MeV

$$\begin{aligned} \gamma + p &\rightarrow \Delta^{++} + \pi^- , \\ \Delta^{++} &\rightarrow p + \pi^+ , \end{aligned} \quad (13)$$

whereas the production cross section of other isobar components  $(\frac{3}{2}, \frac{3}{2})$  are small and can be neglected. The Dubna INC uses the Lindenbaum-Sternheimer resonance model [54] to simulate the reaction (13). In this model, the mass of the isobar  $M$  is determined from the distribution

$$\frac{dW}{dM} \sim F(E, M) \sigma(M) , \quad (14)$$

where  $E$  is the total energy of the system,  $F$  is the two-body phase space of the isobar and  $\pi^-$  meson, and  $\sigma$  is the isobar production cross section which is assumed to be equal to the cross section for elastic  $\pi^+ p$  scattering.

The c.m. emission angle of the isobar is approximated using Eqs. (11) and (12) with the coefficients  $a_{nk}$  listed in Tab. 3 of Ref. [48]; isotropy of the decay of the isobar in its c.m. system is assumed.

In order to calculate the kinematics of the non-resonant part of the reaction (8) and the two remaining three-body channels (9) and (10), the Dubna INC uses the statistical model. The total energies of the two particles (pions) in the c.m. system are determined from the distribution

$$\frac{dW}{dE_{\pi_1} dE_{\pi_2}} \sim (E - E_{\pi_1} - E_{\pi_2}) E_{\pi_1} E_{\pi_2} / E, \quad (15)$$

and that of the third particle (nucleon,  $N$ ) from conservation of energy. The actual simulation of such reactions is done as follows: Using a random number  $\xi$ , we simulate in the beginning the energy of the first pion using

$$E_{\pi_1} = m_{\pi_1} + \xi(E_{\pi_1}^{max} - m_{\pi_1}),$$

where

$$E_{\pi_1}^{max} = [E^2 + m_{\pi_1}^2 - (m_{\pi_2} + m_N)^2] / 2E.$$

Then, we simulate the energy of the second pion  $E_{\pi_2}$  according to Eq. (15) using the Monte-Carlo rejection method. The energy of the nucleon is calculated as  $E_N = E - E_{\pi_1} - E_{\pi_2}$ , following which we check that the “triangle law” for momenta

$$|p_{\pi_1} - p_{\pi_2}| \leq p_N \leq |p_{\pi_1} + p_{\pi_2}|$$

is fulfilled, otherwise this sampling is rejected and the procedure is repeated. The angles  $\Theta$  and  $\varphi$  of the pions are sampled assuming an isotropic distribution of particles in the c.m. system,

$$\cos \Theta_{\pi_1} = 2\xi_1 - 1, \quad \cos \Theta_{\pi_2} = 2\xi_2 - 1, \quad \varphi_{\pi_1} = 2\pi\xi_3, \quad \varphi_{\pi_2} = 2\pi\xi_4,$$

and the angles of the nucleon are defined from momentum conservation,  $\vec{p}_N = -(\vec{p}_{\pi_1} + \vec{p}_{\pi_2})$ . More details on our new approximations for differential elementary cross sections may be found in [18, 19].

The Pauli exclusion principle at the cascade stage of the reaction is handled by assuming that nucleons of the target occupy all the energy levels up to the Fermi energy. Each simulated elastic or inelastic interaction of the projectile (or of a cascade particle) with a nucleon of the target is considered forbidden if the “secondary” nucleons have energies smaller than the Fermi energy. If they do, the trajectory of the particle is traced further from the forbidden point and a new interaction point, a new partner and a new interaction mode are simulated for the traced particle, *etc.*, until the Pauli principle is satisfied or the particle leaves the nucleus.

In this version of the INC, the kinetic energy of the cascade particles is increased or decreased as they move from one of the seven potential regions (zones) to another, but their directions remain unchanged. That is, in our calculations, refraction or reflection of cascade nucleons at potential boundaries is neglected. CEM03.01 allows us to take into account refractions and reflections of cascade nucleons at potential boundaries; for this, one needs to change the value of the parameter **irefrac** from 0 to 1 in the subroutine **initial**. But this option provides somewhat worse overall agreement of calculations with some experimental data, therefore the option of no refractions/reflections was chosen as the default in CEM03.01.

This INC does not take into account the so-called “trawling” effect [3]. That is, in the beginning of the simulation of each event, the nuclear density distributions for the protons and

neutrons of the target are calculated according to Eq. (1) and a subsequent decrease of the nuclear density with the 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 may be neglected at incident energies below about 5 GeV in the case of heavy targets like actinides and below about 1 GeV for light targets like carbon. At higher incident energies the progressive decrease of nuclear density with the development of the intranuclear cascade has a strong influence on the calculated characteristics and this effect has to be taken into account [3]. Therefore, in transport codes that use as event generators both CEM03.01 and our high-energy code LAQGSM03.01 [20], we recommend simulating nuclear reactions with CEM03.01 at incident energies up to about 1 GeV for light nuclei like C and up to about 5 GeV for actinide nuclei, and to switch to simulations using LAQGSM03.01, which considers the “trawling” effect, at higher energies of transported particles.

An important ingredient of the CEM is the criterion for transition from the intranuclear cascade to the preequilibrium model. In conventional cascade-evaporation models (like ISABEL and Bertini’s INC used in MCNPX [37], fast particles are traced down to some minimal energy, the cutoff energy  $T_{cut}$  (or one compares the duration of the cascade stage of a reaction with a cutoff time, in “time-like” INC models, such as the Liege INC [51]). This cutoff is usually less than  $\simeq 10$  MeV above the Fermi energy, below which particles are considered to be absorbed by the nucleus. The CEM uses a different criterion to decide when a primary particle is considered to have left the cascade.

An effective local optical absorptive potential  $W_{opt. mod.}(r)$  is defined from the local interaction cross section of the particle, including Pauli-blocking effects. This imaginary potential is compared to one defined by a phenomenological global optical model  $W_{opt. exp.}(r)$ . We characterize the degree of similarity or difference of these imaginary potentials by the parameter

$$\mathcal{P} = | (W_{opt. mod.} - W_{opt. exp.}) / W_{opt. exp.} | . \quad (16)$$

When  $\mathcal{P}$  increases above an empirically chosen value, the particle leaves the cascade, and is then considered to be an exciton. From a physical point of view, such a smooth transition from the cascade stage of the reaction seems to be more attractive than the “sharp cut-off” method. In addition, as was shown in Ref. [2], this improves the agreement between the calculated and experimental spectra of secondary nucleons, especially at low incident energies and backward angles of the detected nucleons (see *e.g.*, Figs. 3 and 11 of Ref. [2]). More details about this can be found in [2, 14, 55].

CEM03.01 uses a fixed value  $\mathcal{P} = 0.3$  (at incident energies below 100 MeV), just as all its predecessors did. With this value, we find that the cascade stage of the CEM is generally shorter than that in other cascade models. This fact leads to an overestimation of preequilibrium particle emission at incident energies above about 150 MeV, and correspondingly to an underestimation of neutron production from such reactions, as was established in Ref. [14]. In Ref. [14], this problem was solved temporarily in a very rough way by using the transition from the INC to the preequilibrium stage according to Eq. (16) when the incident energy of the projectile is below 150 MeV, and by using the “sharp cut-off” method with a cutoff energy  $T_{cut} = 1$  MeV for higher incident energies. This “ad hoc” rough criterion solved the problem of underestimating neutron production at high energies, providing meanwhile a reasonably good description of reactions below 150 MeV. But it provides an unphysical discontinuity in some observables calculated by MCNPX using CEM2k [14] as an event generator, observed but not understood by Broeders and Konobeev [56]. In CEM03.01, this problem is solved by using a

smooth transition from the first criterion to the second one in the energy interval from 75 to 225 MeV, so that no discontinuities are produced in results from CEM03.01.

Beside the changes to the Dubna INC mentioned above, we also made in the INC a number of other improvements and refinements, such as imposing momentum-energy conservation for each simulated event (the Monte-Carlo algorithm previously used in the CEM provided momentum-energy conservation only statistically, on the average, but not exactly for each simulated event) and using real binding energies for nucleons in the cascade instead of the approximation of a constant separation energy of 7 MeV used in previous versions of the CEM. We have also improved many algorithms used in the Monte-Carlo simulations in many subroutines, decreasing the computing time by up to a factor of 6 for heavy targets, which is very important when performing practical simulations with transport codes like MCNPX or MARS.

Let us mention that in the CEM the initial configuration for the preequilibrium decay (number of excited particles and holes, *i.e.* excitons  $n_0 = p_0 + h_0$ , excitation energy  $E_0^*$ , linear momentum  $\mathbf{P}_0$ , and angular momentum  $\mathbf{L}_0$  of the nucleus) differs significantly from that usually postulated in exciton models. Our calculations [2, 57, 58] have shown that the distributions of residual nuclei remaining after the cascade stage of the reaction, *i.e.* before the preequilibrium emission, with respect to  $n_0$ ,  $p_0$ ,  $h_0$ ,  $E_0^*$ ,  $\mathbf{P}_0$ , and  $\mathbf{L}_0$  are rather broad.<sup>2</sup>

## 2.2. The Coalescence Model

When the cascade stage of a reaction is completed, CEM03.01 uses the coalescence model described in Refs. [59, 60] to “create” high-energy  $d$ ,  $t$ ,  ${}^3\text{He}$ , and  ${}^4\text{He}$  by final-state interactions among emitted cascade nucleons, already outside of the target nucleus. In contrast to most other coalescence models for heavy-ion induced reactions, where complex particle spectra are estimated simply by convolving the measured or calculated inclusive spectra of nucleons with corresponding fitted coefficients (see, *e.g.*, [61] and references therein), CEM03.01 uses in its simulation of particle coalescence real information about all emitted cascade nucleons and does not use integrated spectra. CEM03.01 assumes that all the cascade nucleons having differences in their momenta smaller than  $p_c$  and the correct isotopic content form an appropriate composite particle. This means that the formation probability for, *e.g.* a deuteron is

$$W_d(\vec{p}, b) = \int \int d\vec{p}_p d\vec{p}_n \rho^C(\vec{p}_p, b) \rho^C(\vec{p}_n, b) \delta(\vec{p}_p + \vec{p}_n - \vec{p}) \Theta(p_c - |\vec{p}_p - \vec{p}_n|), \quad (17)$$

where the particle density in momentum space is related to the one-particle distribution function  $f$  by

$$\rho^C(\vec{p}, b) = \int d\vec{r} f^C(\vec{r}, \vec{p}, b). \quad (18)$$

Here,  $b$  is the impact parameter for the projectile interacting with the target nucleus and the superscript index  $C$  shows that only cascade nucleons are taken into account for the coalescence

---

<sup>2</sup>Unfortunately, this fact was misunderstood by the authors of the code HETC-3STEP [44]. In spite of the fact that it has been stressed explicitly, and figures with distributions of excited nuclei after the cascade stage of a reaction with respect to the number of excitons and other characteristics were shown in a number of publications (see, *e.g.*, Fig. 5 in Ref. [2], Fig. 1 in Ref. [58], p. 109 in Ref. [57], and p. 706 in Ref. [22]), the authors of Ref. [44] misstated this fact as “*Gudima et al. assumed the state of two particles and one hole at the beginning ... Hence, their assumption is not valid for the wide range of incident energy*”, claiming this as a weakness of the CEM and a priority of the code HETC-3STEP, where smooth distributions of excited nuclei after the cascade stage of reactions with respect to  $n_0$  are used. This had already been done in the CEM [1, 2].

process. The coalescence radii  $p_c$  were fitted for each composite particle in Ref. [59] to describe available data for the reaction Ne+U at 1.04 GeV/nucleon, but the fitted values turned out to be quite universal and were subsequently found to satisfactorily describe high-energy complex-particle production for a variety of reactions induced both by particles and nuclei at incident energies up to about 200 GeV/nucleon, when describing nuclear reactions with the Los Alamos version of the Quark-Gluon String Model (LAQGSM) [20, 62] or with its predecessor, the Quark-Gluon String Model (QGSM) [63]. These parameters are:

$$p_c(d) = 90 \text{ MeV}/c; \quad p_c(t) = p_c(^3\text{He}) = 108 \text{ MeV}/c; \quad p_c(^4\text{He}) = 115 \text{ MeV}/c. \quad (19)$$

As the INC of CEM03.01 is different from those of LAQGSM or QGSM, it is natural to expect different best values for  $p_c$  as well. Our recent studies show that the values of parameters  $p_c$  defined by Eq. (19) are also good for CEM03.01 for projectile particles with kinetic energies  $T_0$  lower than 300 MeV and equal to or above 1 GeV. For incident energies in the interval  $300 \text{ MeV} < T_0 \leq 1 \text{ GeV}$ , a better overall agreement with the available experimental data is obtained by using values of  $p_c$  equal to 150, 175, and 175 MeV/c for  $d$ ,  $t(^3\text{He})$ , and  $^4\text{He}$ , respectively. These values of  $p_c$  are fixed as defaults in CEM03.01. If several cascade nucleons are chosen to coalesce into composite particles, they are removed from the distributions of nucleons and do not contribute further to such nucleon characteristics as spectra, multiplicities, *etc.*

### 2.3. Preequilibrium Reactions

The subsequent preequilibrium interaction stage of nuclear reactions is considered by the CEM in the framework of an extension of the Modified Exciton Model (MEM) [5, 6]. At the preequilibrium stage of a reaction we take into account all possible nuclear transitions changing the number of excitons  $n$  with  $\Delta n = +2, -2$ , and 0, as well as all possible multiple subsequent emissions of  $n$ ,  $p$ ,  $d$ ,  $t$ ,  $^3\text{He}$ , and  $^4\text{He}$ . The corresponding system of master equations describing the behavior of a nucleus at the preequilibrium stage is solved by the Monte-Carlo technique [1, 2].

For a preequilibrium nucleus with excitation energy  $E$  and number of excitons  $n = p + h$ , the partial transition probabilities changing the exciton number by  $\Delta n$  are

$$\lambda_{\Delta n}(p, h, E) = \frac{2\pi}{\hbar} |M_{\Delta n}|^2 \omega_{\Delta n}(p, h, E). \quad (20)$$

The emission rate of a nucleon of the type  $j$  into the continuum is estimated according to the detailed balance principle

$$\begin{aligned} \Gamma_j(p, h, E) &= \int_{V_j^c}^{E-B_j} \lambda_c^j(p, h, E, T) dT, \\ \lambda_c^j(p, h, E, T) &= \frac{2s_j + 1}{\pi^2 \hbar^3} \mu_j \Re_j(p, h) \frac{\omega(p-1, h, E-B_j-T)}{\omega(p, h, E)} T \sigma_{inv}(T), \end{aligned} \quad (21)$$

where  $s_j$ ,  $B_j$ ,  $V_j^c$ , and  $\mu_j$  are the spin, binding energy, Coulomb barrier, and reduced mass of the emitted particle, respectively. The factor  $\Re_j(p, h)$  ensures the condition for the exciton chosen to be the particle of type  $j$  and can easily be calculated by the Monte-Carlo technique.

Assuming an equidistant level scheme with the single-particle density  $g$ , we have the level density of the  $n$ -exciton state as [64]

$$\omega(p, h, E) = \frac{g(gE)^{p+h-1}}{p!h!(p+h-1)!} . \quad (22)$$

This expression should be substituted into Eq. (21). For the transition rates (20), one needs the number of states taking into account the selection rules for intranuclear exciton-exciton scattering. The appropriate formulae have been derived by Williams [65] and later corrected for the exclusion principle and indistinguishability of identical excitons in Refs. [66, 67]:

$$\begin{aligned} \omega_+(p, h, E) &= \frac{1}{2}g \frac{[gE - \mathcal{A}(p+1, h+1)]^2}{n+1} \left[ \frac{gE - \mathcal{A}(p+1, h+1)}{gE - \mathcal{A}(p, h)} \right]^{n-1} , \\ \omega_0(p, h, E) &= \frac{1}{2}g \frac{[gE - \mathcal{A}(p, h)]}{n} [p(p-1) + 4ph + h(h-1)] , \\ \omega_-(p, h, E) &= \frac{1}{2}gph(n-2) , \end{aligned} \quad (23)$$

where  $\mathcal{A}(p, h) = (p^2 + h^2 + p - h)/4 - h/2$ . By neglecting the difference of matrix elements with different  $\Delta n$ ,  $M_+ = M_- = M_0 = M$ , we estimate the value of  $M$  for a given nuclear state by associating the  $\lambda_+(p, h, E)$  transition with the probability for quasi-free scattering of a nucleon above the Fermi level on a nucleon of the target nucleus. Therefore, we have

$$\frac{\langle \sigma(v_{rel})v_{rel} \rangle}{V_{int}} = \frac{\pi}{\hbar} |M|^2 \frac{g[gE - \mathcal{A}(p+1, h+1)]}{n+1} \left[ \frac{gE - \mathcal{A}(p+1, h+1)}{gE - \mathcal{A}(p, h)} \right]^{n-1} . \quad (24)$$

Here,  $V_{int}$  is the interaction volume estimated as  $V_{int} = \frac{4}{3}\pi(2r_c + \lambda/2\pi)^3$ , with the de Broglie wave length  $\lambda/2\pi$  corresponding to the relative velocity  $v_{rel} = \sqrt{2T_{rel}/m_N}$ . A value of the order of the nucleon radius is used for  $r_c$  in the CEM:  $r_c = 0.6$  fm.

The averaging in the left-hand side of Eq. (24) is carried out over all excited states taking into account the Pauli principle in the approximation

$$\langle \sigma(v_{rel})v_{rel} \rangle \simeq \langle \sigma(v_{rel}) \rangle \langle v_{rel} \rangle . \quad (25)$$

The averaged cross section  $\langle \sigma(v_{rel}) \rangle$  is calculated by the Monte-Carlo simulation method and by introducing a factor  $\eta$  effectively taking into account the Pauli principle exactly as is done in the Fermi-gas model (see, *e.g.*, [68])<sup>3</sup>

$$\sigma(v_{rel}) = \frac{1}{2}[\sigma_{pp}(v_{rel}) + \sigma_{pn}(v_{rel})]\eta(T_F/T) , \text{ where} \quad (26)$$

$$\eta(x) = \begin{cases} 1 - \frac{7}{2}x, & \text{if } x \leq 0.5 , \\ 1 - \frac{7}{5}x + \frac{2}{5}x(2 - \frac{1}{x})^{5/2}, & \text{if } x > 0.5 . \end{cases} \quad (27)$$

Here,  $v_{rel}$  is the relative velocity of the excited nucleon (exciton) and the target nucleon in units of the speed of light and  $T$  is the kinetic energy of the exciton. The free-particle interaction

---

<sup>3</sup>Unfortunately, formula (27) as presented in Ref. [2] had some misprints; in the prior publication [1], it was correct.

cross sections  $\sigma_{pp}(v_{rel})$  and  $\sigma_{pn}(v_{rel})$  in Eq. (26) are estimated using the relations suggested by Metropolis *et al.* [69]

$$\begin{aligned}\sigma_{pp}(v_{rel}) &= \frac{10.63}{v_{rel}^2} - \frac{29.92}{v_{rel}} + 42.9 , \\ \sigma_{pn}(v_{rel}) &= \frac{34.10}{v_{rel}^2} - \frac{82.2}{v_{rel}} + 82.2 ,\end{aligned}\tag{28}$$

where the cross sections are given in mb.

The relative kinetic energy of colliding particles necessary to calculate  $\langle v_{rel} \rangle$  and the factor  $\eta$  in Eqs. (26,27) are estimated in the so-called “right-angle collision” approximation [5], *i.e.* as a sum of the mean kinetic energy of an excited particle (exciton) measured from the bottom of the potential well  $T_p = T_F + E/n$  plus the mean kinetic energy of an intranuclear nucleon partner  $T_N = 3T_F/5$ , that is  $T_{rel} = T_p + T_N = 8T_F/5 + E/n$ .

Combining (20), (22) and (24), we get finally for the transition rates:

$$\begin{aligned}\lambda_+(p, h, E) &= \frac{\langle \sigma(v_{rel})v_{rel} \rangle}{V_{int}} , \\ \lambda_0(p, h, E) &= \frac{\langle \sigma(v_{rel})v_{rel} \rangle}{V_{int}} \frac{n+1}{n} \left[ \frac{gE - \mathcal{A}(p, h)}{gE - \mathcal{A}(p+1, h+1)} \right]^{n+1} \frac{p(p-1) + 4ph + h(h-1)}{gE - \mathcal{A}(p, h)} , \\ \lambda_-(p, h, E) &= \frac{\langle \sigma(v_{rel})v_{rel} \rangle}{V_{int}} \left[ \frac{gE - \mathcal{A}(p, h)}{gE - \mathcal{A}(p+1, h+1)} \right]^{n+1} \frac{ph(n+1)(n-2)}{[gE - \mathcal{A}(p, h)]^2} .\end{aligned}\tag{29}$$

CEM considers the possibility of fast  $d$ ,  $t$ ,  $^3\text{He}$ , and  $^4\text{He}$  emission at the preequilibrium stage of a reaction in addition to the emission of nucleons. We assume that in the course of a reaction  $p_j$  excited nucleons (excitons) are able to condense with probability  $\gamma_j$  forming a complex particle which can be emitted during the preequilibrium state. A modification of Eq. (21) for the complex-particle emission rates is described in detail in Refs. [1, 2]. The “condensation” probability  $\gamma_j$  is estimated in those references as the overlap integral of the wave function of independent nucleons with that of the complex particle (cluster)

$$\gamma_j \simeq p_j^3 (V_j/V)^{p_j-1} = p_j^3 (p_j/A)^{p_j-1} .\tag{30}$$

This is a rather crude estimate. In the usual way the values  $\gamma_j$  are taken from fitting the theoretical preequilibrium spectra to the experimental ones, which gives rise to an additional, as compared to (30), dependence of the factor  $\gamma_j$  on  $p_j$  and excitation energy (see, *e.g.*, Refs. [70, 71]), for each considered reaction.

The single-particle density  $g_j$  for complex particle states is found in the CEM by assuming the complex particles move freely in a uniform potential well whose depth is equal to the binding energy of this particle in a nucleus [2]

$$g_j(T) = \frac{V(2s_j+1)(2\mu_j)^{3/2}}{4\pi^2\hbar^3} (T+B_j)^{1/2} .\tag{31}$$

As we stated previously, this is a crude approximation and it does not provide a good prediction of emission of preequilibrium  $\alpha$  particles (see, *e.g.*, [55] and references therein). In CEM03.01, to improve the description of preequilibrium complex-particle emission, we estimate  $\gamma_j$  by multiplying the estimate provided by Eq. (30) by an empirical coefficient  $M_j(A, Z, T_0)$  whose values are fitted to available nucleon-induced experimental complex-particle spectra. We

fix the fitted values of  $M_j(A, Z, T_0)$  in data commons of CEM03.01 and complement them with routines **gambetn** and **gambetp** for their interpolation outside the region covered by our fitting. As shown in one example in Fig. 6 of Appendix 3, after fitting  $M_j(A, Z, T_0)$ , CEM03.01 describes quite well the measured spectra of all complex particles, providing a much better agreement with experimental data than all its predecessors did.

The CEM predicts forward peaked (in the laboratory system) angular distributions for preequilibrium particles. For instance, CEM03.01 assumes that a nuclear state with a given excitation energy  $E^*$  should be specified not only by the exciton number  $n$  but also by the momentum direction  $\Omega$ . Following Ref. [72], the master equation (11) from Ref. [2] can be generalized for this case provided that the angular dependence for the transition rates  $\lambda_+$ ,  $\lambda_0$ , and  $\lambda_-$  (Eq. (29)) is factorized. In accordance with Eqs. (24) and (25), in the CEM it is assumed that

$$\langle \sigma \rangle \rightarrow \langle \sigma \rangle F(\Omega) , \quad (32)$$

where

$$F(\Omega) = \frac{d\sigma^{free}/d\Omega}{\int d\Omega' d\sigma^{free}/d\Omega'} . \quad (33)$$

The scattering cross section  $d\sigma^{free}/d\Omega$  is assumed to be isotropic in the reference frame of the interacting excitons, thus resulting in an asymmetry in both the nucleus center-of-mass and laboratory frames. The angular distributions of preequilibrium complex particles are assumed [2] to be similar to those for the nucleons in each nuclear state.

This calculational scheme is easily realized by the Monte-Carlo technique. It provides a good description of double differential spectra of preequilibrium nucleons and a not-so-good but still satisfactory description of complex-particle spectra from different types of nuclear reactions at incident energies from tens of MeV to several GeV. For incident energies below about 200 MeV, Kalbach [73] has developed a phenomenological systematics for preequilibrium-particle angular distributions by fitting available measured spectra of nucleons and complex particles. As the Kalbach systematics are based on measured spectra, they describe very well the double-differential spectra of preequilibrium particles and generally provide a better agreement of calculated preequilibrium complex particle spectra with data than does the CEM approach based on Eqs. (32,33). This is why we have incorporated into CEM03.01 the Kalbach systematics [73] to describe angular distributions of both preequilibrium nucleons and complex particles at incident energies up to 210 MeV. At higher energies, we use in CEM03.01 the CEM approach based on Eqs. (32,33).

By “preequilibrium particles” we mean particles which are emitted after the cascade stage of a reaction but before achieving statistical equilibrium at a time  $t_{eq}$ , which is fixed by the condition  $\lambda_+(n_{eq}, E) = \lambda_-(n_{eq}, E)$  from which we get

$$n_{eq} \simeq \sqrt{2gE} . \quad (34)$$

At  $t \geq t_{eq}$  (or  $n \geq n_{eq}$ ), the behavior of the remaining excited compound nucleus is described in the framework of both the Weisskopf-Ewing statistical theory of particle evaporation [74] and fission competition according to Bohr-Wheeler theory [75].

The parameter  $g$  entering into Eqs. (29) and (34) is related to the level-density parameter of single-particle states  $a = \pi^2 g/6$ . At the preequilibrium stage, we calculate the level-density parameter  $a$  with our own approximation [13] in the form proposed initially by Ignatyuk *et al.*

[76], following the method by Iljinov *et al.* [77]:

$$a(Z, N, E^*) = \tilde{a}(A) \left\{ 1 + \delta W_{gs}(Z, N) \frac{f(E^* - \Delta)}{E^* - \Delta} \right\}, \quad (35)$$

where

$$\tilde{a}(A) = \alpha A + \beta A^{2/3} B_s \quad (36)$$

is the asymptotic Fermi-gas value of the level density parameter at high excitation energies. Here,  $B_s$  is the ratio of the surface area of the nucleus to the surface area of a sphere of the same volume (for the ground state of a nucleus,  $B_s \approx 1$ ), and

$$f(E) = 1 - \exp(-\gamma E). \quad (37)$$

$E^*$  is the total excitation energy of the nucleus, related to the “thermal” energy  $U$  by:  $U = E^* - E_R - \Delta$ , where  $E_R$  and  $\Delta$  are the rotational and pairing energies, respectively.

We use the shell correction  $\delta W_{gs}(Z, N)$  by Möller *et al.* [78] and the pairing energy shifts from Möller, Nix, and Kratz [79]. The values of the parameters  $\alpha$ ,  $\beta$ , and  $\gamma$  were derived in Ref. [13] by fitting the the same data analyzed by Iljinov *et al.* [77] (we discovered that Iljinov *et al.* used  $11/\sqrt{A}$  for the pairing energies  $\Delta$  in deriving their level-density systematics instead of the value of  $12/\sqrt{A}$  stated in Ref. [77] and we also found several misprints in the nuclear level-density data shown in their Tables. 1 and 2 used in the fit). We find:

$$\alpha = 0.1463, \beta = -0.0716, \text{ and } \gamma = 0.0542.$$

As mentioned in Section 2.2, the standard version of the CEM [2] provides an overestimation of preequilibrium particle emission from different p+A and A+A reactions we have analyzed (see more details in [14, 15]). One way to solve this problem suggested in Ref. [14] is to change the criterion for the transition from the cascade stage to the preequilibrium one, as described in Section 2.2. Another easy way suggested in Ref. [14] to shorten the preequilibrium stage of a reaction is to arbitrarily allow only transitions that increase the number of excitons,  $\Delta n = +2$ , *i.e.*, only allow the evolution of a nucleus toward the compound nucleus. In this case, the time of the equilibration will be shorter and fewer preequilibrium particles will be emitted, leaving more excitation energy for the evaporation. Such a “never-come-back” approach is used by some other exciton models, for instance, by the Multistage Preequilibrium Model (MPM) used in LAHET [80] and by FLUKA [81]. This approach was used in the CEM2k [14] version of the CEM and it allowed us to describe much better the p+A reactions measured at GSI in inverse kinematics at energies around 1 GeV/nucleon. Nevertheless, the “never-come-back” approach seems unphysical, therefore we no longer use it. We now address the problem of emitting fewer preequilibrium particles in the CEM by following Veselský [82]. We assume that the ratio of the number of quasiparticles (excitons)  $n$  at each preequilibrium reaction stage to the number of excitons in the equilibrium configuration  $n_{eq}$ , corresponding to the same excitation energy, to be a crucial parameter for determining the probability of preequilibrium emission  $P_{pre}$ . This probability for a given preequilibrium reaction stage is evaluated using the formula

$$P_{pre}(n/n_{eq}) = 1 - \exp\left(-\frac{(n/n_{eq} - 1)}{2\sigma_{pre}^2}\right) \quad (38)$$

for  $n \leq n_{eq}$  and equal to zero for  $n > n_{eq}$ . The basic assumption leading to Eq. (38) is that  $P_{pre}$  depends exclusively on the ratio  $n/n_{eq}$  as can be deduced from the results of Böhning [83]

where the density of particle-hole states is approximately described using a Gaussian centered at  $n_{eq}$ . The parameter  $\sigma_{pre}$  is a free parameter and we assume no dependence on excitation energy [82]. Our calculations of several reactions using different values of  $\sigma_{pre}$  show that an overall reasonable agreement with available data can be obtained using  $\sigma_{pre} = 0.4$ – $0.5$  (see Fig. 11 in Ref. [15]). In CEM03.01, we choose the fixed value  $\sigma_{pre} = 0.4$  and use Eqs. (34,38) as criteria for the transition from the preequilibrium stage of reactions to evaporation, instead of using the “never-come-back” approach along with Eq. (34), as was done in CEM2k.

## 2.4. Evaporation

CEM03.01 uses an extension of the Generalized Evaporation Model (GEM) code GEM2 by Furihata [84]–[86] after the preequilibrium stage of reactions to describe evaporation of nucleons, complex particles, and light fragments heavier than  $^4\text{He}$  (up to  $^{28}\text{Mg}$ ) from excited compound nuclei and to describe their fission, if the compound nuclei are heavy enough to fission ( $Z \geq 65$ ). The GEM is an extension by Furihata of the Dostrovsky evaporation model [87] as implemented in LAHET [80] to include up to 66 types of particles and fragments that can be evaporated from an excited compound nucleus plus a modification of the version of Atchison’s fission model [88, 89] used in LAHET. Many of the parameters were adjusted by Furihata for a better description of fission reactions when using it in conjunction with the extended evaporation model.

A very detailed description of the GEM, together with a large amount of results obtained for many reactions using the GEM coupled either with the Bertini or ISABEL INC models in LAHET may be found in [84, 85]. Therefore, we present here only the main features of the GEM, following mainly [85] and using as well information obtained in private communications with Dr. Furihata.

Furihata did not change in the GEM the general algorithms used in LAHET to simulate evaporation and fission. The decay widths of evaporated particles and fragments are estimated using the classical Weisskopf-Ewing statistical model [74]. In this approach, the decay probability  $P_j$  for the emission of a particle  $j$  from a parent compound nucleus  $i$  with the total kinetic energy in the center-of-mass system between  $\epsilon$  and  $\epsilon + d\epsilon$  is

$$P_j(\epsilon)d\epsilon = g_j\sigma_{inv}(\epsilon)\frac{\rho_d(E - Q - \epsilon)}{\rho_i(E)}\epsilon d\epsilon, \quad (39)$$

where  $E$  [MeV] is the excitation energy of the parent nucleus  $i$  with mass  $A_i$  and charge  $Z_i$ , and  $d$  denotes a daughter nucleus with mass  $A_d$  and charge  $Z_d$  produced after the emission of ejectile  $j$  with mass  $A_j$  and charge  $Z_j$  in its ground state.  $\sigma_{inv}$  is the cross section for the inverse reaction,  $\rho_i$  and  $\rho_d$  are the level densities  $[\text{MeV}]^{-1}$  of the parent and the daughter nucleus, respectively.  $g_j = (2S_j + 1)m_j/\pi^2\hbar^2$ , where  $S_j$  is the spin and  $m_j$  is the reduced mass of the emitted particle  $j$ . The  $Q$ -value is calculated using the excess mass  $M(A, Z)$  as  $Q = M(A_j, Z_j) + M(A_d, Z_d) - M(A_i, Z_i)$ . In GEM2, four mass tables are used to calculate  $Q$ -values, according to the following priorities, where a lower priority table is only used outside the range of validity of the higher priority one: (1) the Audi-Wapstra mass table [90], (2) theoretical masses calculated by Möller *et al.* [78], (3) theoretical masses calculated by Comay *et al.* [91], (4) the mass excess calculated using the old Cameron formula [92]. As does LAHET, GEM2 uses Dostrovsky’s formula [87] to calculate the inverse cross section  $\sigma_{inv}$  for all emitted

particles and fragments

$$\sigma_{inv}(\epsilon) = \sigma_g \alpha \left( 1 + \frac{\beta}{\epsilon} \right), \quad (40)$$

which is often written as

$$\sigma_{inv}(\epsilon) = \begin{cases} \sigma_g c_n (1 + b/\epsilon) & \text{for neutrons} \\ \sigma_g c_j (1 - V/\epsilon) & \text{for charged particles,} \end{cases}$$

where  $\sigma_g = \pi R_b^2$  [fm<sup>2</sup>] is the geometrical cross section, and

$$V = k_j Z_j Z_d e^2 / R_c \quad (41)$$

is the Coulomb barrier in MeV.

One new ingredient in GEM2 in comparison with LAHET, which considers evaporation of only 6 particles (n, p, d, t, <sup>3</sup>He, and <sup>4</sup>He), is that Furihata includes the possibility of evaporation of up to 66 types of particles and fragments and incorporates into GEM2 several alternative sets of parameters  $b$ ,  $c_j$ ,  $k_j$ ,  $R_b$ , and  $R_c$  for each particle type.

The 66 ejectiles considered by GEM2 for evaporation are selected to satisfy the following criteria: (1) isotopes with  $Z_j \leq 12$ ; (2) naturally existing isotopes or isotopes near the stability line; (3) isotopes with half-lives longer than 1 ms. All the 66 ejectiles considered by GEM2 are shown in Table 1.

Table 1. The evaporated particles considered by GEM2

$Z_j$	Ejectiles							
0	n							
1	p	d	t					
2	<sup>3</sup> He	<sup>4</sup> He	<sup>6</sup> He	<sup>8</sup> He				
3	<sup>6</sup> Li	<sup>7</sup> Li	<sup>8</sup> Li	<sup>9</sup> Li				
4	<sup>7</sup> Be	<sup>9</sup> Be	<sup>10</sup> Be	<sup>11</sup> Be	<sup>12</sup> Be			
5	<sup>8</sup> B	<sup>10</sup> B	<sup>11</sup> B	<sup>12</sup> B	<sup>13</sup> B			
6	<sup>10</sup> C	<sup>11</sup> C	<sup>12</sup> C	<sup>13</sup> C	<sup>14</sup> C	<sup>15</sup> C	<sup>16</sup> C	
7	<sup>12</sup> N	<sup>13</sup> N	<sup>14</sup> N	<sup>15</sup> N	<sup>16</sup> N	<sup>17</sup> N		
8	<sup>14</sup> O	<sup>15</sup> O	<sup>16</sup> O	<sup>17</sup> O	<sup>18</sup> O	<sup>19</sup> O	<sup>20</sup> O	
9	<sup>17</sup> F	<sup>18</sup> F	<sup>19</sup> F	<sup>20</sup> F	<sup>21</sup> F			
10	<sup>18</sup> Ne	<sup>19</sup> Ne	<sup>20</sup> Ne	<sup>21</sup> Ne	<sup>22</sup> Ne	<sup>23</sup> Ne	<sup>24</sup> Ne	
11	<sup>21</sup> Na	<sup>22</sup> Na	<sup>23</sup> Na	<sup>24</sup> Na	<sup>25</sup> Na			
12	<sup>22</sup> Mg	<sup>23</sup> Mg	<sup>24</sup> Mg	<sup>25</sup> Mg	<sup>26</sup> Mg	<sup>27</sup> Mg	<sup>28</sup> Mg	

GEM2 includes several options for the parameter set in expressions (40,41):

1) The “simple” parameter set is given as  $c_n = c_j = k_j = 1$ ,  $b = 0$ , and  $R_b = R_c = r_0(A_j^{1/3} + A_d^{1/3})$  [fm]; users need to input  $r_0$ .

2) The “precise” parameter set is used in GEM2 as the default, and we use this set in our present work.

A) For all light ejectiles up to  $\alpha$  ( $A_j \leq 4$ ), the parameters determined by Dostrovsky *et al.* [87] are used in GEM2, namely:  $c_n = 0.76 + c_a A_d^{-1/3}$ ,  $b = (b_a A_d^{-2/3} - 0.050)/(0.76 + c_a A_d^{-1/3})$  (and  $b = 0$  for  $A_d \geq 192$ ), where  $c_a = 1.93$  and  $b_a = 1.66$ ,  $c_p = 1 + c$ ,  $c_d = 1 + c/2$ ,  $c_t = 1 + c/3$ ,  $c_{3He} = c_\alpha = 0$ ,  $k_p = k$ ,  $k_d = k + 0.06$ ,  $k_t = k + 0.12$ ,  $k_{3He} = k_\alpha - 0.06$ , where  $c$ ,  $k$ , and  $k_\alpha$

are listed in Table 2 for a set of  $Z_d$ . Between the  $Z_d$  values listed in Table 2,  $c$ ,  $k$ , and  $k_\alpha$  are interpolated linearly. The nuclear distances are given by  $R_b = 1.5A^{1/3}$  for neutrons and protons, and  $1.5(A_d^{1/3} + A_j^{1/3})$  for d, t,  $^3\text{He}$ , and  $\alpha$ .

Table 2.  $k$ ,  $k_\alpha$ , and  $c$  parameters used in GEM2

$Z_d$	$k$	$k_\alpha$	$c$
$\leq 20$	0.51	0.81	0.0
30	0.60	0.85	-0.06
40	0.66	0.89	-0.10
$\geq 50$	0.68	0.93	-0.10

The nuclear distance for the Coulomb barrier is expressed as  $R_c = R_d + R_j$ , where  $R_d = r_0^c A^{1/3}$ ,  $r_0^c = 1.7$ , and  $R_j = 0$  for neutrons and protons, and  $R_j = 1.2$  for d, t,  $^3\text{He}$ , and  $^4\text{He}$ . We note that several of these parameters are similar to the original values published by Dostrovsky *et al.* [87] but not exactly the same. Dostrovsky *et al.* [87] had  $c_a = 2.2$ ,  $b_a = 2.12$ , and  $r_0^c = 1.5$ . Also, for the  $k$ ,  $k_\alpha$ , and  $c$  parameters shown in Table 2, they had slightly different values, shown in Table 3.

Table 3.  $k_p$ ,  $c_p$ ,  $k_\alpha$ , and  $c_\alpha$  parameters from Ref. [87]

$Z_d$	$k_p$	$c_p$	$k_\alpha$	$c_\alpha$
10	0.42	0.50	0.68	0.10
20	0.58	0.28	0.82	0.10
30	0.68	0.20	0.91	0.10
50	0.77	0.15	0.97	0.08
$\geq 70$	0.80	0.10	0.98	0.06

B) For fragments heavier than  $\alpha$  ( $A_j \geq 4$ ), the “precise” parameters of GEM2 use values by Matsuse *et al.* [93], namely:  $c_j = k = 1$ ,  $R_b = R_0(A_j) + R_0(A_d) + 2.85$  [fm],  $R_c = R_0(A_j) + R_0(A_d) + 3.75$  [fm], where  $R_0(A) = 1.12A^{1/3} - 0.86A^{-1/3}$ .

3) The code GEM2 contains two other options for the parameters of the inverse cross sections.

A) A set of parameters due to Furihata for light ejectiles in combination with Matsuse’s parameters for fragments heavier than  $\alpha$ . Furihata and Nakamura determined  $k_j$  for p, d, t,  $^3\text{He}$ , and  $\alpha$  as follows [86]:

$$k_j = c_1 \log(Z_d) + c_2 \log(A_d) + c_3.$$

The coefficients  $c_1$ ,  $c_2$ , and  $c_3$  for each ejectile are shown in Table 4.

Table 4.  $c_1$ ,  $c_2$ , and  $c_3$  for p, d, t,  $^3\text{He}$ , and  $\alpha$  from [86]

Ejectile	$c_1$	$c_2$	$c_3$
p	0.0615	0.0167	0.3227
d	0.0556	0.0135	0.4067
t	0.0530	0.0134	0.4374
$^3\text{He}$	0.0484	0.0122	0.4938
$\alpha$	0.0468	0.0122	0.5120

When these parameters are chosen in GEM2, the following nuclear radius  $R$  is used in the calculation of  $V$  and  $\sigma_g$ :

$$R = \begin{cases} 0 & \text{for } A = 1, \\ 1.2 & \text{for } 2 \leq A \leq 4, \\ 2.02 & \text{for } 5 \leq A \leq 6, \\ 2.42 & \text{for } A = 7, \\ 2.83 & \text{for } A = 8, \\ 3.25 & \text{for } A = 9, \\ 1.414A_d^{1/3} + 1 & \text{for } A \geq 10. \end{cases}$$

B) The second new option in GEM2 is to use Furihata's parameters for light ejectiles up to  $\alpha$  and the Botvina *et al.* [94] parameterization for inverse cross sections for heavier ejectiles. Botvina *et al.* [94] found that  $\sigma_{inv}$  can be expressed as

$$\sigma_{inv} = \sigma_g \begin{cases} (1 - V/\epsilon) & \text{for } \epsilon \geq V + 1 \text{ [MeV]}, \\ \exp[\alpha(\epsilon - V - 1)]/(V + 1) & \text{for } \epsilon < V + 1 \text{ [MeV]}, \end{cases} \quad (42)$$

where

$$\begin{aligned} \alpha &= 0.869 + 9.91/Z_j, \\ V &= \frac{Z_j Z_d}{r_0^b (A_j^{1/3} + A_d^{1/3})}, \\ r_0^b &= 2.173 \frac{1 + 6.103 \times 10^{-3} Z_j Z_d}{1 + 9.443 \times 10^{-3} Z_j Z_d} \text{ [fm]}. \end{aligned}$$

The expression of  $\sigma_{inv}$  for  $\epsilon < V + 1$  shows the fusion reaction in the sub-barrier region. When using Eq. (42) instead of Eq. (40), the total decay width for a fragment emission can not be calculated analytically. Therefore, the total decay width must be calculated numerically and takes much CPU time.

The total decay width  $\Gamma_j$  is calculated by integrating Eq. (39) with respect to the total kinetic energy  $\epsilon$  from the Coulomb barrier  $V$  up to the maximum possible value,  $(E - Q)$ . The good feature of Dostrovsky's approximation for the inverse cross sections, Eq. (40), is its simple energy dependence that allows the analytic integration of Eq. (39). By using Eq. (40) for  $\sigma_{inv}$ , the total decay width for the particle emission is

$$\Gamma_j = \frac{g_j \sigma_g \alpha}{\rho_i(E)} \int_V^{E-Q} \epsilon \left(1 + \frac{\beta}{\epsilon}\right) \rho_d(E - Q - \epsilon) d\epsilon. \quad (43)$$

The level density  $\rho(E)$  is calculated in GEM2 according to the Fermi-gas model using the expression [95]

$$\rho(E) = \frac{\pi}{12} \frac{\exp(2\sqrt{a(E - \delta)})}{a^{1/4}(E - \delta)^{5/4}}, \quad (44)$$

where  $a$  is the level density parameter and  $\delta$  is the pairing energy in MeV. As does LAHET, GEM2 uses the  $\delta$  values evaluated by Cook *et al.* [96]. For those values not evaluated by Cook *et al.*,  $\delta$ 's from Gilbert and Cameron [95] are used instead. The simplest option for the level-density parameter in GEM2 is  $a = A_d/8$  [MeV<sup>-1</sup>], but the default is the Gilbert-Cameron-Cook-Ignatyuk (GCCCI) parameterization from LAHET [80]:

$$a = \tilde{a} \frac{1 - e^{-u}}{u} + a_I \left(1 - \frac{1 - e^{-u}}{u}\right), \quad (45)$$

where  $u = 0.05(E - \delta)$ , and

$$a_I = (0.1375 - 8.36 \times 10^{-5} A_d) \times A_d,$$

$$\tilde{a} = \begin{cases} A_d/8 & \text{for } Z_d < 9 \text{ or } N_d < 9, \\ A_d(a' + 0.00917S) & \text{for others.} \end{cases}$$

For deformed nuclei with  $54 \leq Z_d \leq 78$ ,  $86 \leq Z_d \leq 98$ ,  $86 \leq N_d \leq 122$ , or  $130 \leq N_d \leq 150$ ,  $a' = 0.12$  while  $a' = 0.142$  for other nuclei. The shell corrections  $S$  is expressed as a sum of separate contributions from neutrons and protons, *i.e.*  $S = S(Z_d) + S(N_d)$  from [95, 96] and are tabulated in [84].

The level density is calculated using Eq. (44) only for high excitation energies,  $E \geq E_x$ , where  $E_x = U_x + \delta$  and  $U_x = 2.5 + 150/A_d$  (all energies are in MeV). At lower excitation energies, the following [95] is used for the level density:

$$\rho(E) = \frac{\pi}{12} \frac{1}{T} \exp((E - E_0)/T), \quad (46)$$

where  $T$  is the nuclear temperature defined as  $1/T = \sqrt{a/U_x} - 1.5/U_x$ . To provide a smooth connection of Eqs. (44) and (46) at  $E = E_x$ ,  $E_0$  is defined as  $E_0 = E_x - T(\log T - 0.25 \log a - 1.25 \log U_x + 2\sqrt{aU_x})$ .

For  $E - Q - V < E_x$ , substituting Eq. (46) into Eq. (44) we can calculate the integral analytically, if we neglect the dependence of the level density parameter  $a$  on  $E$ :

$$\Gamma_j = \frac{\pi g_j \sigma_g \alpha}{12 \rho_i(E)} \{I_1(t, t) + (\beta + V)I_0(t)\}, \quad (47)$$

where  $I_0(t)$  and  $I_1(t, t_x)$  are expressed as

$$\begin{aligned} I_0(t) &= e^{-E_0/T} (e^t - 1), \\ I_1(t, t_x) &= e^{-E_0/T} T \{(t - t_x + 1)e^{t_x} - t - 1\}, \end{aligned}$$

where  $t = (E - Q - V)/T$  and  $t_x = E_x/T$ . For  $E - Q - V \geq E_x$ , the integral of Eq. (43) cannot be solved analytically because of the denominator in Eq. (44). However, it is approximated as

$$\Gamma_j = \frac{\pi g_j \sigma_g \alpha}{12 \rho_i(E)} [I_1(t, t_x) + I_3(s, s_x)e^s + (\beta + V)\{I_0(t_x) - I_2(s, s_x)e^s\}], \quad (48)$$

where  $I_2(s, s_x)$  and  $I_3(s, s_x)$  are given by

$$I_2(s, s_x) = 2\sqrt{2}\{s^{-3/2} + 1.5s^{-5/2} + 3.75s^{-7/2} - (s_x^{-3/2} + 1.5s_x^{-5/2} + 3.75s_x^{-7/2})e^{s_x-s}\},$$

$$\begin{aligned} I_3(s, s_x) &= (\sqrt{2}a)^{-1}[2s^{-1/2} + 4s^{-3/2} + 13.5s^{-5/2} + 60.0s^{-7/2} + 325.125s^{-9/2} \\ &\quad - \{(s^2 - s_x^2)s_x^{-3/2} + (1.5s^2 + 0.5s_x^2)s_x^{-5/2} + (3.75s^2 + 0.25s_x^2)s_x^{-7/2} + (12.875s^2 \\ &\quad + 0.625s_x^2)s_x^{-9/2} + (59.0625s^2 + 0.9375s_x^2)s_x^{-11/2} + (324.8s_x^2 + 3.28s_x^2)s_x^{-13/2}\}e^{s_x-s}], \end{aligned}$$

with  $s = 2\sqrt{a(E - Q - V - \delta)}$  and  $s_x = 2\sqrt{a(E_x - \delta)}$ .

The particle type  $j$  to be evaporated is selected in GEM2 by the Monte-Carlo method according to the probability distribution calculated as  $P_j = \Gamma_j / \sum_j \Gamma_j$ , where  $\Gamma_j$  is given by Eqs. (47) or (48). The total kinetic energy  $\epsilon$  of the emitted particle  $j$  and the recoil energy of

the daughter nucleus is chosen according to the probability distribution given by Eq. (39). The angular distribution of ejectiles is simulated to be isotropic in the center-of-mass system.

According to Friedman and Lynch [97], it is important to include excited states in the particle emitted via the evaporation process along with evaporation of particles in their ground states, because it greatly enhances the yield of heavy particles. Taking this into consideration, GEM2 includes evaporation of complex particles and light fragments both in the ground states and excited states. An excited state of a fragment is included in calculations if its half-lifetime  $T_{1/2}(s)$  satisfies the following condition:

$$\frac{T_{1/2}}{\ln 2} > \frac{\hbar}{\Gamma_j^*}, \quad (49)$$

where  $\Gamma_j^*$  is the decay width of the excited particle (resonance). GEM2 calculates  $\Gamma_j^*$  in the same manner as for a ground-state particle emission. The  $Q$ -value for the resonance emission is expressed as  $Q^* = Q + E_j^*$ , where  $E_j^*$  is the excitation energy of the resonance. The spin state of the resonance  $S_j^*$  is used in the calculation of  $g_j$ , instead of the spin of the ground state  $S_j$ . GEM2 uses the ground state masses  $m_j$  for excited states because the difference between the masses is negligible.

Instead of treating a resonance as an independent particle, GEM2 simply enhances the decay width  $\Gamma_j$  of the ground state particle emission as follows:

$$\Gamma_j = \Gamma_j^0 + \sum_n \Gamma_j^n, \quad (50)$$

where  $\Gamma_j^0$  is the decay width of the ground state particle emission, and  $\Gamma_j^n$  is that of the  $n$ th excited state of the particle  $j$  emission which satisfies Eq. (49).

The total-kinetic-energy distribution of the excited particles is assumed to be the same as that of the ground-state particle.  $S_j^*$ ,  $E_j^*$ , and  $T_{1/2}$  used in GEM2 are extracted from the Evaluated Nuclear Structure Data File (ENSDF) database maintained by the National Nuclear Data Center at Brookhaven National Laboratory [98].

Note that when including evaporation of up to 66 particles in GEM2, its running time increases significantly compared to the case when evaporating only 6 particles, up to  $^4\text{He}$ . The major particles emitted from an excited nucleus are n, p, d, t,  $^3\text{He}$ , and  $^4\text{He}$ . For most cases, the total emission probability of particles heavier than  $\alpha$  is negligible compared to those for the emission of light ejectiles. Our detailed study of different reactions (see, *e.g.*, [99] and references therein) shows that if we study only nucleon and complex-particle spectra or only spallation and fission products and are not interested in light fragments, we can consider evaporation of only 6 types of particles in GEM2 and save much time, getting results very close to the ones calculated with the more time consuming “66” option. In CEM03.01, we have introduced an input parameter called **nevtype** that defines the number of types of particles to be considered at the evaporation stage. The index of each type of particle that can be evaporated corresponds to the particle arrangement in Table 1, with values, *e.g.*, of 1, 2, 3, 4, 5, and 6 for n, p, d, t,  $^3\text{He}$ , and  $^4\text{He}$ , with succeeding values up to 66 for  $^{28}\text{Mg}$ . All 66 particles that can possibly evaporate are listed in CEM03.01 together with their mass number, charge, and spin values in the **block data bdejc**. For all ten examples of inputs and outputs of CEM03.01 included in Appendices 1 and 2, whose results are plotted in the figures in Appendix 3, we have performed calculations taking into account only 6 types of evaporated particles (**nevtype** = 6) as well as with the “66” option (**nevtype** = 66) and we provide the corresponding computing time

for these examples in the captions to the appropriate figures shown in Appendix 3. The “6” option can be up to several times faster than the “66” option, providing meanwhile almost the same results. Therefore we recommend that users of CEM03.01 use 66 for the value of the input parameter **nevttype** only when they are interested in all fragments heavier than  $^4\text{He}$ ; otherwise, we recommend the default value of 6 for **nevttype**, saving computing time. Alternatively, users may choose intermediate values of **nevttype**, for example 9 if one wants to calculate the production of  $^6\text{Li}$ , or 14 for modeling the production of  $^9\text{Be}$  and lighter fragments and nucleons only, while still saving computing time compared to running the code with the maximum value of 66.

## 2.5. Fission

The fission model used in GEM2 is based on Atchison’s model [88, 89] as implemented in LAHET [80], often referred in the literature as the Rutherford Appleton Laboratory (RAL) fission model, which is where Atchison developed it. In GEM2 there are two choices of parameters for the fission model: one of them is the original parameter set by Atchison [88, 89] as implemented in LAHET [80], and the other is a parameter set developed by Furihata [84, 85].

**2.5.1. Fission Probability.** The Atchison fission model is designed to describe only fission of nuclei with  $Z \geq 70$ . It assumes that fission competes only with neutron emission, *i.e.*, from the widths  $\Gamma_j$  of n, p, d, t,  $^3\text{He}$ , and  $^4\text{He}$ , the RAL code calculates the probability of evaporation of any particle. When a charged particle is selected to be evaporated, no fission competition is taken into account. When a neutron is selected to be evaporated, the code does not actually simulate its evaporation, instead it considers that fission may compete, and chooses either fission or evaporation of a neutron according to the fission probability  $P_f$ . This quantity is treated by the RAL code differently for the elements above and below  $Z = 89$ . The reasons Atchison split the calculation of the fission probability  $P_f$  are: (1) there is very little experimental information on fission in the region  $Z = 85$  to  $88$ , (2) the marked rise in the fission barrier for nuclei with  $Z^2/A$  below about 34 (see Fig. 2 in [89]) together with the disappearance of asymmetric mass splitting, indicates that a change in the character of the fission process occurs. If experimental information were available, a split between regions around  $Z^2/A \approx 34$  would be more sensible [89].

1)  $70 \leq Z_j \leq 88$ . For fissioning nuclei with  $70 \leq Z_j \leq 88$ , GEM2 uses the original Atchison calculation of the neutron emission width  $\Gamma_n$  and fission width  $\Gamma_f$  to estimate the fission probability as

$$P_f = \frac{\Gamma_f}{\Gamma_f + \Gamma_n} = \frac{1}{1 + \Gamma_n/\Gamma_f}. \quad (51)$$

Atchison uses [88, 89] the Weisskopf and Ewing statistical model [74] with an energy-independent pre-exponential factor for the level density (see Eq. (44)) and Dostrovsky’s [87] inverse cross section for neutrons and estimates the neutron width  $\Gamma_n$  as

$$\Gamma_n = 0.352(1.68J_0 + 1.93A_i^{1/3}J_1 + A_i^{2/3}(0.76J_1 - 0.05J_0)), \quad (52)$$

where  $J_0$  and  $J_1$  are functions of the level density parameter  $a_n$  and  $s_n (= 2\sqrt{a_n(E - Q_n - \delta)})$ ,

$$J_0 = \frac{(s_n - 1)e^{s_n} + 1}{2a_n},$$

$$J_1 = \frac{(2s_n^2 - 6s_n + 6)e^{s_n} + s_n^2 - 6}{8a_n^2}.$$

Note that the RAL model uses a fixed value for the level density parameter  $a_n$ , namely

$$a_n = (A_i - 1)/8, \quad (53)$$

and this approximation is kept in GEM2 when calculating the fission probability according to Eq. (51), although it differs from the GCCI parameterization (45) used in GEM2 to calculate particle evaporation widths. The fission width for nuclei with  $70 \leq Z_j \leq 88$  is calculated in the RAL model and in the GEM as

$$\Gamma_f = \frac{(s_f - 1)e^{s_f} + 1}{a_f}, \quad (54)$$

where  $s_f = 2\sqrt{a_f(E - B_f - \delta)}$  and the level density parameter in the fission mode  $a_f$  is fitted by Atchison to describe the measured  $\Gamma_f/\Gamma_n$  to be [89]:

$$a_f = a_n \left( 1.08926 + 0.01098(\chi - 31.08551)^2 \right), \quad (55)$$

and  $\chi = Z^2/A$ . The fission barriers  $B_f$  [MeV] are approximated by

$$B_f = Q_n + 321.2 - 16.7 \frac{Z_i^2}{A} + 0.218 \left( \frac{Z_i^2}{A_i} \right)^2. \quad (56)$$

Note that neither the angular momentum nor the excitation energy of the nucleus are taken into account in finding the fission barriers.

2)  $Z_j \geq 89$ . For heavy fissioning nuclei with  $Z_j \geq 89$  GEM2 follows the RAL model [88, 89] and does not calculate at all the fission width  $\Gamma_f$  and does not use Eq. (51) to estimate the fission probability  $P_f$ . Instead, the following semi-empirical expression obtained by Atchison [88, 89] by approximating the experimental values of  $\Gamma_n/\Gamma_f$  published by Vandenbosch and Huizenga [100] is used to calculate the fission probability:

$$\log(\Gamma_n/\Gamma_f) = C(Z_i)(A_i - A_0(Z_i)), \quad (57)$$

where  $C(Z)$  and  $A_0(Z)$  are constants depending on the nuclear charge  $Z$  only. The values of these constants are those used in the current version of LAHET [80] and are tabulated in Table 5 (note that some adjustments of these values have been done since Atchison's papers [88, 89] were published).

In this approach the fission probability  $P_f$  is independent of the excitation energy of the fissioning nucleus and its angular momentum.

**2.5.2. Mass Distribution.** The selection of the mass of the fission fragments depends on whether the fission is symmetric or asymmetric. For a pre-fission nucleus with  $Z_i^2/A_i \leq 35$ , only symmetric fission is allowed. For  $Z_i^2/A_i > 35$ , both symmetric and asymmetric fission are allowed, depending on the excitation energy of the fissioning nucleus. No new parameters were determined for asymmetric fission in GEM2.

For nuclei with  $Z_i^2/A_i > 35$ , whether the fission is symmetric or not is determined by the asymmetric fission probability  $P_{asy}$

$$P_{asy} = \frac{4870e^{-0.36E}}{1 + 4870e^{-0.36E}}. \quad (58)$$

Table 5.  $C(Z)$  and  $A_0(Z)$  values used in GEM2

Z	$C(Z)$	$A_0(Z)$
89	0.23000	219.40
90	0.23300	226.90
91	0.12225	229.75
92	0.14727	234.04
93	0.13559	238.88
94	0.15735	241.34
95	0.16597	243.04
96	0.17589	245.52
97	0.18018	246.84
98	0.19568	250.18
99	0.16313	254.00
100	0.17123	257.80
101	0.17123	261.30
102	0.17123	264.80
103	0.17123	268.30
104	0.17123	271.80
105	0.17123	275.30
106	0.17123	278.80

**2.5.2.a. Asymmetric fission.** For asymmetric fission, the mass of one of the post-fission fragments  $A_1$  is selected from a Gaussian distribution of mean  $A_f = 140$  and width  $\sigma_M = 6.5$ . The mass of the second fragment is  $A_2 = A_i - A_1$ .

**2.5.2.b. Symmetric fission.** For symmetric fission,  $A_1$  is selected from the Gaussian distribution of mean  $A_f = A_i/2$  and two options for the width  $\sigma_M$  as described below.

The first option for choosing  $\sigma_M$  is the original Atchison approximation:

$$\sigma_M = \begin{cases} 3.97 + 0.425(E - B_f) - 0.00212(E - B_f)^2, \\ 25.27, \end{cases} \quad (59)$$

for  $(E - B_f)$  below or above 100 MeV, respectively. In this expression all values are in MeV and the fission barriers  $B_f$  are calculated according to Eq. (56) for nuclei with  $Z_i \leq 88$ . For nuclei with  $Z_i > 88$ , the expression by Neuzil and Fairhall [101] is used:

$$B_f = C - 0.36(Z_i^2/A_i), \quad (60)$$

where  $C = 18.8, 18.1, 18.1$ , and  $18.5$  [MeV] for odd-odd, even-odd, odd-even, and even-even nuclei, respectively.

The second option in GEM2 for  $\sigma_M$  (used here) was found by Furihata<sup>37,38</sup> as:

$$\sigma_M = C_3(Z_i^2/A_i)^2 + C_4(Z_i^2/A_i) + C_5(E - B_f) + C_6. \quad (61)$$

The constants  $C_3 = 0.122$ ,  $C_4 = -7.77$ ,  $C_5 = 3.32 \times 10^{-2}$ , and  $C_6 = 134.0$  were obtained by fitting with GEM2 the recent Russian collection of experimental fission-fragment mass distributions [102]. In this expression, the fission barriers  $B_f$  by Myers and Swiatecki [103] are used. More details may be found in Ref. [85].

**2.5.3. Charge Distribution.** The charge distribution of fission fragments is assumed to be a Gaussian distribution of mean  $Z_f$  and width  $\sigma_Z$ .  $Z_f$  is expressed as

$$Z_f = \frac{Z_i + Z'_1 - Z'_2}{2}, \quad (62)$$

where

$$Z'_l = \frac{65.5A_l}{131 + A_l^{2/3}}, l = 1 \text{ or } 2. \quad (63)$$

The original Atchison model uses  $\sigma_Z = 2.0$ . An investigation by Furihata [85] suggests that  $\sigma_Z = 0.75$  provides a better agreement with data; therefore  $\sigma_Z = 0.75$  is used in GEM2 and in our code.

**2.5.4. Kinetic Energy Distribution.** The kinetic energy of fission fragments [MeV] is determined by a Gaussian distribution with mean  $\epsilon_f$  and width  $\sigma_{\epsilon_f}$ .

The original parameters in the Atchison model are:

$$\begin{aligned} \epsilon_f &= 0.133Z_i^2/A_i^{1/3} - 11.4, \\ \sigma_{\epsilon_f} &= 0.084\epsilon_f. \end{aligned}$$

Furihata's parameters in the GEM, which we also use, are:

$$\epsilon_f = \begin{cases} 0.131Z_i^2/A_i^{1/3}, \\ 0.104Z_i^2/A_i^{1/3} + 24.3, \end{cases} \quad (64)$$

for  $Z_i^2/A_i^{1/3} \leq 900$  and  $900 < Z_i^2/A_i^{1/3} \leq 1800$ , respectively, according to Rusanov *et al.* [102]. By fitting the experimental data by Itkis *et al.* [104], Furihata found the following expression for  $\sigma_{\epsilon_f}$

$$\sigma_{\epsilon_f} = \begin{cases} C_1(Z_i^2/A_i^{1/3} - 1000) + C_2, \\ C_2, \end{cases} \quad (65)$$

for  $Z_i^2/A_i^{1/3}$  above and below 1000, respectively, and the values of the fitted constants are  $C_1 = 5.70 \times 10^{-4}$  and  $C_2 = 86.5$ . The experimental data used by Furihata for fitting are the values extrapolated to the nuclear temperature 1.5 MeV by Itkis *et al.* [104]. More details may be found in [85].

We note that Atchison has also modified his original version using recent data and published [105] improved (and more complicated) parameterizations for many quantities and distributions in his model, but these modifications [105] have not been included either in LAHET or in GEM2.

**2.5.5. Modifications to GEM2 in CEM03.01.** First, we fixed several observed uncertainties and small errors in the 2002 version of GEM2 Dr. Furihata kindly sent us. Then, we extended GEM2 to describe fission of lighter nuclei, down to  $Z \geq 65$ , and modified it [17] so that it provides a good description of fission cross sections when it is used after our INC and preequilibrium models.

If we had merged GEM2 with the INC and preequilibrium-decay modules of CEM03.01 without any modifications, the new code would not describe correctly fission cross sections (and the yields of fission fragments). This is because Atchison fitted the parameters of his RAL fission model when it followed the Bertini INC [106] which differs from ours. In addition,

Atchison did not model preequilibrium emission. Therefore, the distributions of fissioning nuclei in  $A$ ,  $Z$ , and excitation energy  $E^*$  simulated by Atchison differ significantly from the distributions we get; as a consequence, all the fission characteristics are also different. Furihata used GEM2 coupled either with the Bertini INC [106] or with the ISABEL [107] INC code, which also differs from our INC, and did not include preequilibrium particle emission. Therefore the distributions of fissioning nuclei simulated by Furihata differ from those in our simulations, so the parameters adjusted by Furihata to work well with her INC are not appropriate for us. To get a good description of fission cross sections (and fission-fragment yields) we have modified at least two parameters in GEM2 as used in CEM03.01 (see more details in [15, 16]).

The main parameters that determine the fission cross sections calculated by GEM2 are the level density parameter in the fission channel,  $a_f$  (or more exactly, the ratio  $a_f/a_n$  as calculated by Eq. (55)) for preactinides, and parameter  $C(Z)$  in Eq. (57) for actinides. The sensitivity of results to these parameters is much higher than to either the fission barrier heights used in a calculation or other parameters of the model. Therefore we choose [17] to adjust only these two parameters in our merged code. We do not change the form of systematics (55) and (57) derived by Atchison. We only introduce additional coefficients both to  $a_f$  and  $C(Z)$ , replacing  $a_f \rightarrow C_a \times a_f$  in Eq. (55) and  $C(Z_i) \rightarrow C_c \times C(Z_i)$  in Eq. (57) and fit  $C_a$  and  $C_c$  to experimental proton-induced fission cross sections covered by Prokofiev's systematics [108]. No other parameters in GEM2 have been changed. For preactinides, we fit only  $C_a$ . The values of  $C_a$  found in our fit to Prokofiev's systematics are close to one and vary smoothly with the proton energy and the charge or mass number of the target. This result gives us some confidence in our procedure, and allows us to interpolate the values of  $C_a$  for nuclei and incident proton energies not analyzed by Prokofiev. For actinides, as described in [15, 16], we have to fit both  $C_a$  and  $C_c$ . The values of  $C_a$  we find are also very close to one, while the values of  $C_c$  are more varied, but both of them change smoothly with the proton energy and  $Z$  or  $A$  of the target, which again allows us to interpolate them for nuclei and energies outside Prokofiev's systematics.

We fix the fitted values of  $C_a$  and  $C_c$  in data blocks in our code and use the routines **fitafpa** and **fitafac** to interpolate to nuclei not covered by Prokofiev's systematics. We believe that such a procedure provides a reasonably accurate fission cross section calculation, at least for proton energies and target nuclei not too far from the ones covered by the systematics.

## 2.6. The Fermi Break-Up Model

After calculating the coalescence stage of a reaction, CEM03.01 moves to the description of the last slow stages of the interaction, namely to preequilibrium decay and evaporation, with a possible competition of fission. But as mentioned above, if the residual nuclei have atomic numbers with  $A < 13$ , CEM03.01 uses the Fermi break-up model [109] to calculate their further disintegration instead of using the preequilibrium and evaporation models.

All formulas and details of the algorithms used in the version of the Fermi break-up model developed in the former group of Prof. Barashenkov at Joint Institute for Nuclear Research (JINR), Dubna, Russia and released in CEM03.01 may be found in [38]. All the information needed to calculate the break-up of an excited nucleus is its excitation energy  $U$  and the mass and charge numbers  $A$  and  $Z$ . The total energy of the nucleus in the rest frame will be  $E = U + M(A, Z)$ , where  $M$  is the mass of the nucleus. The total probability per unit time for a nucleus to break up into  $n$  components in the final state (*e.g.*, a possible residual nucleus,

nucleons, deuterons, tritons, alphas, *etc.*) is given by

$$W(E, n) = (V/\Omega)^{n-1} \rho_n(E), \quad (66)$$

where  $\rho_n$  is the density of final states,  $V$  is the volume of the decaying system and  $\Omega = (2\pi\hbar)^3$  is the normalization volume. The density  $\rho_n(E)$  can be defined as a product of three factors:

$$\rho_n(E) = M_n(E) S_n G_n. \quad (67)$$

The first one is the phase space factor defined as

$$M_n(E) = \int_{-\infty}^{+\infty} \cdots \int_{-\infty}^{+\infty} \delta \left( \sum_{b=1}^n \vec{p}_b \right) \delta \left( E - \sum_{b=1}^n \sqrt{p^2 + m_b^2} \right) \prod_{b=1}^n d^3 p_b, \quad (68)$$

where  $\vec{p}_b$  are fragment momenta. The second one is the spin factor

$$S_n = \prod_{b=1}^n (2s_b + 1), \quad (69)$$

which gives the number of states with different spin orientations. The last one is the permutation factor

$$G_n = \prod_{j=1}^k \frac{1}{n_j!}, \quad (70)$$

which takes into account identical particles in the final state ( $n_j$  is the number of components of  $j$ -type particles and  $k$  is defined by  $n = \sum_{j=1}^k n_j$ ). For example, if we have in the final state six particles ( $n = 6$ ) and two of them are alphas, three are nucleons, and one is a deuteron, then  $G_6 = 1/(2!3!1!) = 1/12$ . For the non-relativistic case, the integration in Eq. (68) can be evaluated analytically (see, *e.g.*, [38]) and the probability for a nucleus to disintegrate into  $n$  fragments with masses  $m_b$ , where  $b = 1, 2, 3, \dots, n$  is

$$W(E, n) = S_n G_n \left( \frac{V}{\Omega} \right)^{n-1} \left( \frac{1}{\sum_{b=1}^n m_b} \prod_{b=1}^n m_b \right)^{3/2} \frac{(2\pi)^{3(n-1)/2}}{\Gamma(3(n-1)/2)} E^{(3n-5)/2}, \quad (71)$$

where  $\Gamma(x)$  is the gamma function.

The angular distribution of  $n$  emitted fragments is assumed to be isotropic in the c.m. system of the disintegrating nucleus and their kinetic energies are calculated from momentum-energy conservation. The Monte-Carlo method is used to randomly select the decay channel according to probabilities defined by Eq. (71). Then, for a given channel, CEM03.01 calculates kinematical quantities for each fragment according to the  $n$ -body phase space distribution using Kopylov's method [110]. Generally, CEM03.01 considers formation of fragments only in their ground and those low-lying states which are stable for nucleon emission. However, several unstable fragments with large lifetimes:  $^5\text{He}$ ,  $^5\text{Li}$ ,  $^8\text{Be}$ ,  $^9\text{B}$ , *etc.* are considered as well. The randomly chosen channel will be allowed to decay only if the total kinetic energy  $E_{kin}$  of all fragments at the moment of break-up is positive, otherwise a new simulation will be performed and a new channel will be selected. The total kinetic energy  $E_{kin}$  can be calculated according to the equation:

$$E_{kin} = U + M(A, Z) - E_{Coulomb} - \sum_{b=1}^n (m_b + \epsilon_b), \quad (72)$$

where  $m_b$  and  $\epsilon_b$  are masses and excitation energies of fragments, respectively, and  $E_{Coulomb}$  is the Coulomb barrier for the given channel. It is approximated by

$$E_{Coulomb} = \frac{3}{5} \frac{e^2}{r_0} \left(1 + \frac{V}{V_0}\right)^{-1/3} \left( \frac{Z^2}{A^{1/3}} - \sum_{b=1}^n \frac{Z_b^2}{A_b^{1/3}} \right), \quad (73)$$

where  $A_b$  and  $Z_b$  are the mass number and the charge of the  $b$ -th particle of a given channel, respectively.  $V_0$  is the volume of the system corresponding to normal nuclear density and  $V = kV_0$  is the decaying system volume (we assume  $k = 1$  in CEM03.01).

Thus, the Fermi break-up model used here has only one free parameter,  $V$  or  $V_0$ , the volume of decaying system, which is estimated as follows:

$$V = 4\pi R^3/3 = 4\pi r_0^3 A/3, \quad (74)$$

where we use  $r_0 = 1.4$  fm. This parameter is used to calculate the quantity **bl** in the routine **gitab**.

There is no limitation on the number  $n$  of fragments a nucleus may break up into in our version of the break-up model, in contrast to implementations in other codes, such as  $n \leq 3$  in MCNPX, or  $n \leq 7$  in LAHET.

## 2.7. Total Reaction Cross Sections (Normalization)

CEM03.01 (just like many other INC-based models) calculates the total reaction cross section,  $\sigma_{in}$ , by the Monte-Carlo method using the geometrical cross section,  $\sigma_{geom}$ , and the number of inelastic,  $N_{in}$ , and elastic,  $N_{el}$ , simulated events, namely:  $\sigma_{in} = \sigma_{geom} N_{in} / (N_{in} + N_{el})$ . The value of the total reaction cross section calculated this way is printed in the beginning of the CEM03.01 output labeled as *Monte Carlo inelastic cross section*. This approach provides a good agreement with available data for reactions induced by nucleons, pions, and photons at incident energies above about 100 MeV, but is not reliable enough at energies below 100 MeV (see, *e.g.*, Fig. 4 and Ref. [16] and Figs. 4 and 5 in Ref. [19]).

To address this problem, we have incorporated [16] into CEM03.01 the NASA systematics by Tripathi *et al.* [111] for all incident protons and for neutrons with energies above the maximum in the NASA reaction cross sections, and the Kalbach systematics [112] for neutrons of lower energy. For reactions induced by monochromatic and bremsstrahlung photons, we incorporate into CEM03.01 [19] the recent systematics by Kossov [113]. Details on these systematics together with examples of several total inelastic cross sections calculated with them compared with available experimental data may be found in [16, 19]. Our analysis of many different reactions has shown that at incident energies below about 100 MeV these systematics generally describe the total inelastic cross sections better than the Monte-Carlo method does, and no worse than the Monte-Carlo method at higher energies. Therefore we choose these systematics as the default for normalization of all CEM03.01 results. The total reaction cross sections calculated by these systematics are printed in the CEM03.01 output labeled as *Inelastic cross section used here*. (Of course, users may renormalize all the CEM03.01 results to the Monte-Carlo total reaction cross sections by making a small change to the code in the subroutine **typeout**).

## Acknowledgments

We are grateful to Dr. Shiori Furihata for providing to us her Generalized Evaporation/fission Model code GEM2 which we have incorporated into CEM03.01, several useful discussions, and allowing us to use GEM2 in our codes and to distribute it further to other users without needing further permission. We thank Dr. Helder Duarte for providing us with numerical values of experimental cross sections from his collection, useful discussions, and help. We thank Dr. Kumataro Ukai for providing us with numerical values of single-pion photoproduction cross sections from their compilation [114]. We thank Prof. Koh Sakamoto and Drs. Hiroshi Matsumura, Hiromitsu Haba, and Yasuji Oura for providing us with their publications and numerical tables of their measured data, as well as for useful discussions, help in creating several figures for us, and their interest in our modeling. We thank Dr. Igor Pshenichnov for sending us the  $\gamma - p$  and  $\gamma - n$  event generators from their Moscow photonuclear reaction INC [53]; we use a small portion of a large data file developed for this code in CEM03.01.

We thank Drs. Arjan Koning, Nathalie Marie-Nourry, Valentin Blideanu, Alain Letourneau, Yury Titarenko, Vechaslav Batyaev, Vitaly Pronskikh, Carmen Villagrasa-Canton, Alexander Prokofief, Anatoly Ignatyuk, and Satoshi Chiba for providing us with tabulated values of many of their measurements and experimental data by other authors from their collections, which we have used while developing CEM03.01.

Last but not least, we express our gratitude to many colleagues, in particular Drs. Richard Prael, Robert Little, Alexandra Heath, Mark Chadwick, Laurie Waters, Tony Gabriel, Franz Gallmeier, Jerry Nolen, Richard Olsher, and Igor Moskalenko, for useful discussions, interest in and support of our work.

This work was supported by the US Department of Energy, Moldovan-US Bilateral Grants Program, CRDF Projects MP2-3025 and MP2-3045, and the NASA ATP01 Grant NRA-01-01-ATP-066.

## References

- [1] K. K. Gudima, S. G. Mashnik, and V. D. Toneev, “Cascade-Exciton Model of Nuclear Reactions: Model Formulation,” JINR Communication P2-80-774, Dubna (1980); “Cascade-Exciton Model of Nuclear Reactions: Comparison with Experiment,” JINR Communication P2-80-777, Dubna (1980).
- [2] K. K. Gudima, S. G. Mashnik, and V. D. Toneev, “Cascade-Exciton Model of Nuclear Reactions,” Nucl. Phys. **A401** (1983) 329–361.
- [3] V. S. Barashenkov and V. D. Toneev, *Interaction of High Energy Particle and Nuclei with Atomic Nuclei*, Atomizdat, Moscow (1972).
- [4] V. S. Barashenkov, A. S. Iljinov, N. M. Sobolevskii, and V. D. Toneev, “Interaction of Particles and Nuclei of High and Ultrahigh Energy with Nuclei,” Usp. Fiz. Nauk **109**, (1973) 91–136 [Sov. Phys. Usp. **16** (1973) 31–52].
- [5] K. K. Gudima, G. A. Ososkov, and V. D. Toneev, “Model for Pre-Equilibrium Decay of Excited Nuclei,” Yad. Fiz. **21** (1975) 260–272 [Sov. J. Nucl. Phys. **21** (1975) 138–143].
- [6] S. G. Mashnik and V. D. Toneev, “MODEX—the Program for Calculation of the Energy Spectra of Particles Emitted in the Reactions of Pre-Equilibrium and Equilibrium Statistical Decays,” JINR Communication P4-8417, Dubna (1974).

- [7] T. Gabriel, G. Maino, and S. G. Mashnik, “Analysis of Intermediate Energy Photonuclear Reactions,” JINR Preprint E2-94-424, Dubna (1994); Proc. XII Int. Sem. on High Energy Phys. Problems *Relativistic Nuclear Physics & Quantum Chromodynamics*, Dubna, Russia, September 12–17, 1994, Eds. A. M. Baldin and V. V. Burov, Dubna, JINR Publish Department, 1997, JINR E1,2-97-79, pp. 309–318.
- [8] S. G. Mashnik, “Cascade-Exciton Model Analysis of Excitation Functions for Proton-Induced Reactions at Low and Intermediate Energies, *Izv. RAN, Ser. Fiz.* **60** (1996) 73–84 [*Bull. of the Russian Acad. Sci., Physics*, **60** (1996) 58–67].
- [9] S. G. Mashnik, “User Manual for the Code CEM95,” (1995), Bogoliubov Laboratory of Theoretical Physics, Joint Institute for Nuclear Research, Dubna, Russia; OECD Nuclear Energy Agency Data Bank, Le Seine Saint-Germain 12, Boulevard des Iles, F-92130 Issy-les-Moulineaux, Paris, France <http://www.nea.fr/abs/html/iaea1247.html>; Radiation Safety Information Computational Center (RSICC), Oak Ridge, USA, <http://www-rsicc.ornl.gov/codes/psr/psr3/psr-357.html>.
- [10] M. Blann, H. Gruppelaar, P. Nagel, and J. Rodens, *International Code Comparison for Intermediate Energy Nuclear Data*, NEA OECD, Paris (1994).
- [11] P. Nagel, J. Rodens, M. Blann, and H. Gruppelaar, “Intermediate Energy Nuclear Reaction Code Intercomparison: Application to Transmutation of Long-Lived Reactor Wastes,” *Nucl. Sci. Eng.* **119** (1995) 97–107.
- [12] S. G. Mashnik and A. J. Sierk, “Improved Cascade-Exciton Model of Nuclear Reactions,” LANL Report LA-UR-98-5999 (1998); E-print: nucl-th/9812069; Proc. SARE-4, Knoxville, TN, September 13–16, 1998, edited by Tony A. Gabriel (ORNL, 1999), pp. 29–51.
- [13] A. J. Sierk and S. G. Mashnik, “Modeling Fission in the Cascade-Exciton Model,” LANL Report LA-UR-98-5998 (1998); E-print: nucl-th/9812070; Proc. SARE-4, Knoxville, TN, September 13–16, 1998, edited by Tony A. Gabriel (ORNL, 1999), pp. 53–67.
- [14] S. G. Mashnik and A. J. Sierk, “CEM2k—Recent Developments in CEM,” Proc. AccApp00, November 12–16, 2000, Washington, DC (USA), American Nuclear Society, La Grange Park, IL, 2001, pp. 328–341; E-print: nucl-th/0011064.
- [15] S. G. Mashnik, K. K. Gudima, and A. J. Sierk, “Merging the CEM2k and LAQGSM Codes with GEM2 to Describe Fission and Light-Fragment Production,” LANL Report LA-UR-03-2261, Los Alamos (2003); E-print: nucl-th/0304012; Proc. SATIF-6, April 10–12, 2002, Stanford Linear Accelerator Center, CA 94025, USA, (NEA/OECD, Paris, France, 2004), pp. 337–366.
- [16] Stepan G. Mashnik, Arnold J. Sierk, and Konstantin K. Gudima, “Complex Particle and Light Fragment Emission in the Cascade-Exciton Model of Nuclear Reactions,” LANL Report LA-UR-02-5185, Los Alamos (2002); E-print: nucl-th/0208048.
- [17] M. Baznat, K. Gudima, and S. Mashnik, “Proton-Induced Fission Cross Section Calculation with the LANL Codes CEM2k+GEM2 and LAQGSM+GEM2,” LANL Report LA-UR-03-3750, Los Alamos (2003); Proc. AccApp03, San Diego, California, June 1–5, 2003, (ANS, La Grange Park, IL 60526, USA, 2004), pp. 976–985; E-print: nucl-th/0307014.

- [18] S. G. Mashnik, K. K. Gudima, A. J. Sierk, and R. E. Prael, “Improved Intranuclear Cascade Models for the Codes CEM2k and LAQGSM,” LA-UR-05-0711, Los Alamos (2005); E-print: nucl-th/0502019; Proc. ND2004, September 26–October 1, 2004, Santa Fe, NM, USA, edited by R. C. Haight, M. B. Chadwick, T. Kawano, and P. Talou, (AIP Conference Proceedings, Volume 769, Melville, New York, 2005), pp. 1188–1192.
- [19] S. G. Mashnik, M. I. Baznat, K. K. Gudima, A. J. Sierk, and R. E. Prael, “Extension of the CEM2k and LAQGSM Codes to Describe Photo-Nuclear Reactions,” LANL Report LA-UR-05-2013, Los Alamos (2005), E-print: nucl-th/0503061, to be published in Journal of Nuclear and Radiochemical Science, Vol. 6, No. 2, 2005.
- [20] S. G. Mashnik, K. K. Gudima, M. I. Baznat, A. J. Sierk, R. E. Prael, and N. V. Mokhov, “CEM03.01 and LAQGSM03.01 Versions of the Improved Cascade-Exciton Model (CEM) and Los Alamos Quark-Gluon String Model (LAQGSM) Codes,” LANL Research Note X-5-RN (U) 05-11, LA-UR-05-2686 (2005).
- [21] M. G. Gornov, Yu. B. Gurov, A. L. Iljin, S. G. Mashnik, P. V. Morokhov, V. A. Pechkurov, M. A. Polikarpov, V. I. Saveliev, F. M. Sergeev, S. A. Smirnov, A. A. Khomutov, B. A. Chernyshev, R. R. Shafigullin, and A. V. Shishkov, “Emission of Protons on Absorption of Stopped Negative Pions by *Be*, *C*, *Si*, *Cu*, and *Ge* Nuclei,” *Yad. Fiz.* **47** (1988) 959–967 [*Sov. J. Nucl. Phys.* **47** (1988) 612–617]; “Emission of Composite Particles in the Absorption of Stopped Negative Pions by Nuclei of *Be*, *C*, *Si*, *Cu*, and *Ge*,” *Yad. Fiz.* **47** (1988) 1193–1200 [*Sov. J. Nucl. Phys.* **47** (1988) 760–764]; [http://www.osti.gov/energycitations/product.biblio.jsp?osti\\_id=6721591&query\\_id=0](http://www.osti.gov/energycitations/product.biblio.jsp?osti_id=6721591&query_id=0).
- [22] S. G. Mashnik, “Neutron-Induced Particle Production in the Cumulative and Noncumulative Regions at Intermediate Energies,” *Nucl. Phys.* **A568** (1994) 703–726.
- [23] S. G. Mashnik, R. J. Peterson, A. J. Sierk, and M. R. Braunstein. “Pion-Induced Transport of  $\pi$  Mesons in Nuclei,” *Phys. Rev. C* **61** (2000) 034601.
- [24] R. J. Peterson, S. de Barros, H. Schechter, A. G. DaSilva, J. C. Suita, and S. G. Mashnik, “Fission Probabilities Across the  $\pi$ -Nucleon Delta Resonance,” *Euro. Phys. J. A* **10** (2001) 69–71. A. V. Prokofiev, S. G. Mashnik, and A. J. Sierk, “Cascade-Exciton Model Analysis of Nucleon-Induced Fission Cross Sections of Lead and Bismuth at Energies from 45 to 500 MeV,” *Nucl. Sci. Eng.* **131** (1999) 78–95.
- [25] Yu. E. Titarenko, O. V. Shvedov, V. F. Batyaev, E. I. Karpikhin, V. M. Zhivun, A. B. Koldobsky, R. D. Mulambetov, S. V. Kvasova, A. N. Sosnin, S. G. Mashnik, R. E. Prael, A. J. Sierk, T. A. Gabriel, M. Saito, and H. Yasuda, “Cross Sections for Nuclide Production in 1 GeV Proton-Irradiated  $^{208}\text{Pb}$ ,” *Phys. Rev. C* **65** (2002) 064610.
- [26] K. A. Van Riper, S. G. Mashnik, and W. B. Wilson, “A Computer Study of Radionuclide Production in High Power Accelerators for Medical and Industrial Applications,” *Nucl. Instr. Meth. A* **463** (2001) 576–585.
- [27] S. G. Mashnik, K. K. Gudima, I. V. Moskalenko, R. E. Prael, and A. J. Sierk, “CEM2k and LAQGSM as Event Generators for Space-Radiation-Shielding and Cosmic-Ray-Propagation Applications,” *Advances in Space Research* **34** (2004) 1288–1296.

- [28] C. Y. Fu, T. A. Gabriel, and R. A. Lillie, “PICA95: an Intranuclear-Cascade Code for 25 MeV to 3.5 GeV Photon-Induced Nuclear Reactions,” Proc. 3rd Specialists Meeting on Shielding Aspects of Accelerators, Targets and Irradiation Facilities (SATIF-3), Tohoku University, Sendai, Japan, May 12–13, 1997, NEA/OECD, 1998, pp. 49–60; [http://www.osti.gov/bridge/product.biblio.jsp?osti\\_id=474922](http://www.osti.gov/bridge/product.biblio.jsp?osti_id=474922).
- [29] T. Sato, K. Shin, S. Ban, T. A. Gabriel, C. Y. Fu, and H. S. Lee, “PICA3, an Updated Code of Photo-Nuclear Cascade Evaporation Code PICA95, and Its Benchmark Experiments,” Proc. MC2000, Lisbon, Portugal, 2000, edited by A. Kling, F. J. C. Barão, M. Nakagawa, L. Távora, and P. Vaz, Springer, Berlin, (2001), pp. 1139–1144.
- [30] A. V. Ignatyuk, N. T. Kulagin, V. P. Lunev, and K.-H. Schmidt, “Analysis of Spallation Residues within the Intranuclear Cascade Model,” Proc. XV Workshop on Physics of Nuclear Fission, Obninsk, 3–6 October, 2000, [www-w2k.gsi.de/charms/Preprints/Obninsk2000/Cascado-v7.pdf](http://www-w2k.gsi.de/charms/Preprints/Obninsk2000/Cascado-v7.pdf).
- [31] A. V. Ignatyuk, N. T. Kulagin, V. P. Lunev, Yu. N. Shubin, N. N. Titarenko, V. F. Batyaev, Yu. E. Titarenko, and V. M. Zhivun, “Analysis of Spallation and Fission Residues for Separated Lead Isotopes Irradiated by Protons at Energies 0.15, 1.0, and 2.6 GeV,” Proc. ND2004, September 26–October 1, 2004, Santa Fe, NM, USA, edited by R. C. Haight, M. B. Chadwick, T. Kawano, and P. Talou, (AIP Conference Proceedings, Volume 769, Melville, New York, 2005), pp. 1307–1312.
- [32] S. Yavshits, G. Boykov, V. Ippolitov, S. Pakhomov, and O. Grudzwvich, “Multiconfiguration Fission Cross Sections at Transitional Energy Region 20–200 MeV,” Voprosy Atomnoj Nauki i Tekhniki, seriya Yadernye Konstanty (Nuclear Constants) **1** (2000) 62–70 (in Russian), translated to English in Report INDC(CCP)-430 (2001), pp. 83–94, <http://www.ippe.obninsk.ru/podrcjd/vant/00-1/1-07.pdf>.
- [33] Zs. Schram, Gy. Kluge, and K. Sailer, “Exciton Cascade Model for Fast Neutron Reactions,” International Atomic Energy Agency Report INDC(HUN)-023/L, Vienna, Austria, June 1987.
- [34] T. Nishida, Y. Nakahara, and T. Tsutsui, “Development of a Nuclear Spallation Simulation Code Calculation of Primary Spallation Products,” *JAERI-M-86-116* (1986) T. Nishida, Y. Nakahara, and T. Tsutsui, “Analysis of the Mass Formula Dependence of the Spallation Product Distribution,” *JAERI-M-87-088* (1987); T. Nishida, H. Takada, and Y. Nakahara, “NUCLEUS,” “Proc. Int. Conf. on Nuclear Data for Science and Technology,” Jülich, Germany, May 13–17, 1991, Ed. S. M. Qaim, “Springer-Verlag”, Berlin (1992), pp. 152–157; H. Takada, Y. Nakahara, T. Nishida, K. Ishibashi, and N. Yoshizawa, “Microscopic Cross Section Calculations with NUCLEUS and HETC-3STEP,” pp. 121–136 in Ref. [10].
- [35] V. S. Barashenkov, Le Van Ngok, L. G. Levchuk, Zh. Zh. Musul’manbekov, A. N. Sosnin, V. D. Toneev and S. Yu. Shmakov, “Cascade Program Complex for Monte-Carlo Simulation of Nuclear Processes Initiated by High Energy Particles and Nuclei in Gaseous and Condensed Matter,” JINR Report R2-85-173, Dubna (1985);

- [36] N. V. Mokhov, “The MARS Code System User’s Guide,” Fermilab-FN-628, 1995; more references and many details on MARS may be found at the Web page <http://www-ap.fnal.gov/MARS/>.
- [37] *MCNPX User’s Manual, Version 2.3.0*, Laurie S. Waters, Editor, LANL Report LA-UR-02-2607 (April, 2002); more references and many details on MCNPX may be found at the Web page <http://mcnpx.lanl.gov/>.
- [38] Nikolai Amelin, *Physics and Algorithms of the Hadronic Monte-Carlo Event Generators. Notes for a Developer*, CERN/IT/ASD Report CERN/IT/99/6, Geneva, Switzerland and JINR/LHE, Dubna, Russia; *Geant4 User’s Documents, Physics Reference Manual*, December 8, 1998, [http://wwwinfo.cern.ch/asd/geant/geant4\\_public/G4UsersDocuments/Overview/html/index.html/](http://wwwinfo.cern.ch/asd/geant/geant4_public/G4UsersDocuments/Overview/html/index.html/).
- [39] V. Lara, “Object-Oriented Approach to Preequilibrium and Equilibrium Decays in Geant4,” Proc. MC2000, Lisbon, Portugal, 2000, edited by A. Kling, F. J. C. Barão, M. Nakagawa, L. Távara, and P. Vaz, Springer, Berlin, (2001), pp. 1039–1044; Vichente Lara and Johannes Peter Wellisch, “Preequilibrium and Equilibrium Decays in Geant4,” [chep2000.pd.infn.it/short\\_p/spa\\_a096.pdf](http://chep2000.pd.infn.it/short_p/spa_a096.pdf); more references and many details on GEANT4 may be found at the Web page <http://wwwasd.web.cern.ch/wwwasd/geant4/geant4.html>.
- [40] N. M. Sobolevsky, “The SHIELD Code (Version 1996.hadr.0) Short User’s Manual,” CCC-667 SHIELD, RSICC Computer Code Collection, ORNL, 1998; A. V. Dementyev and N. M. Sobolevsky, “SHIELD—Universal Monte Carlo Hadron Transport Code: Scope and Applications,” *Radiation Measurements* **30** (1999) 553–557; more references and many details on SHIELD may be found at the Web pages <http://www.nea.fr/abs/html/iaea1287.html>; <http://www-rsicc.ornl.gov/codes/ccc/ccc6/ccc-667.html>.
- [41] I. I. Degtyarev, A. E. Lokhovitskii, M. A. Maslov, I. A. Yazynin, V. I. Belyakov-Bodin, and A. I. Blokhin, “RTS&T Main Features,” Proc. Fourth Int. Workshop on Simulating Accelerator Radiation Environments (SARE-4), Hyatt Regency, Knoxville, TN, September 13–16, 1998, edited by Tony A. Gabriel, ORNL, 1999, pp. 141–149; I. I. Degtyarev, O. A. Liashenko, I. A. Yazynin, V. I. Belyakov-Bodin, and A. I. Blokhin, “Calculational Estimations of Neutron Yield From ADS Targets,” Proc. of the 2001 Particle Accelerator Conference, Chicago, USA, *Voprosy Atomnoi Nauki i Tekhniki* **01-1** (2001) 2796–2798, [www.ippe.obninsk.ru/podr/cjd/vant/01-1/2-03.pdf](http://www.ippe.obninsk.ru/podr/cjd/vant/01-1/2-03.pdf).
- [42] S. E. Chigrinov, A. I. Kievitskaia, I. L. Rakhno, and C. K. Rutkovskaia, “The Code SONET to Calculate Accelerator Driven System Performance,” Proc. Int. Conf. on Accelerator-Driven Transmutation Technologies and Applications (ADTT’99), Praha, Czech Republic, June 7–11, 1999, paper Mo-O-C12 on the Conference CD-ROM and Web page [http://fjfi.cvut.cz/con\\_adtt99](http://fjfi.cvut.cz/con_adtt99).
- [43] C. Y. Fu and T. A. Gabriel, “CALOR As A Single Code Including A Modular Version of HETC,” Proc. Fourth Int. Workshop on Simulating Accelerator Radiation Environments (SARE-4), Hyatt Regency, Knoxville, TN, September 13–16, 1998, ORNL, 1999, pp. 23–27, [http://www.osti.gov/bridge/product.biblio.jsp?osti\\_id=1769](http://www.osti.gov/bridge/product.biblio.jsp?osti_id=1769); T. A. Gabriel

- and L. A. Carlson, "Charged and Neutral Particle Transport Methods and Applications: The CALOR Code System," Proc. Joint Int. Conf. on Mathematical Methods and Supercomputing for Nuclear Applications, Satatoga Springs, NY, Oct. 6–10, 1997, [http://www.osti.gov/bridge/product.biblio.jsp?osti\\_id=527544](http://www.osti.gov/bridge/product.biblio.jsp?osti_id=527544).
- [44] N. Yoshizawa, K. Ishibashi, and H. Takada, "Development of High Energy Transport Code HETC-3STEP Applicable to the Nuclear Reaction with Incident Energies above 20 MeV," J. Nucl. Sci. Techn. **32** (1995) 601-607; H. Takada, Y. Nakahara, T. Nishida, K. Ishibashi, and N. Yoshizawa, "Microscopic Cross Section Calculations with NUCLEUS and HETC-3STEP," pp. 121–136 in Ref. [10].
  - [45] V. S. Barashenkov, A. Yu. Konobeev, Yu. A. Korovin, and V. N. Sosnin, "CASCADE/INPE Code System," Atomnaya Energiya **87** (1999) 283–286 [Atomic Energy **87** (1999) 742–744].
  - [46] A. V. Sannikov and E. N. Savitskaya, "Physics of the HADRON Code: Recent Status and Comparison with Experiment," Nucl. Instr. Meth. A **450** (2000) 127–137.
  - [47] K. K. Gudima, A. S. Iljinov, and V. D. Toneev, "A Cascade Model for Photonuclear Reactions," Communication JINR P2-4661, Dubna (1969).
  - [48] V. S. Barashenkov, F. G. Geregi, A. S. Iljinov, G. G. Jonsson, and V. D. Toneev, "A Cascade-Evaporation Model for Photonuclear Reactions," Nucl. Phys. **A231** (1974) 462–476.
  - [49] J. S. Levinger, "The High Energy Nuclear Photoeffect," Phys. Rev. **84** (1951) 43–51; *Nuclear Photo-Disintegration* (Oxford University Press, 1960); Phys. Lett. B **82**, (1979) 181–182.
  - [50] W. O. Lock and D. F. Measday, *Intermediate Energy Nuclear Physics*, London, Methuen; [Distributed in the U.S.A. by Barnes and Noble, 1970].
  - [51] J. Cugnon, C. Volant, and S. Vuillier, "Improved Intranuclear Cascade Model for Nucleon-Nucleus Interactions," Nucl. Phys. **A620** (1997) 475–509; Th. Aoust and J. Cugnon, "Effects of Isospin and Energy Dependences of the Nuclear Mean Field in Spallation Reactions," Eur. Phys. J. A **21** (2004) 79–85.
  - [52] Helder Duarte, "An Intranuclear Cascade Model for High Energy Transport Codes," Proc. Int. Conf. on Accelerator-Driven Transmutation Technologies and Applications (ADTT'99), Praha, Czech Republic, June 7–11, 1999, paper Mo-O-C17 on the Conference CD-ROM and Web page [http://fjfi.cvut.cz/con\\_adtt99](http://fjfi.cvut.cz/con_adtt99).
  - [53] A. S. Iljinov, I. A. Pshenichnov, N. Bianchi, E. De Sanctis, V. Muccifora, M. Mirazita, and P. Rossi, "Extension of the Intranuclear Cascade Model for Photonuclear Reactions at Energies up to 10 GeV," Nucl. Phys. **A616** (1997) 575–605.
  - [54] S. J. Lindenbaum and R. M. Sternheimer, "Isobaric Nucleon Model for Pion Production in Nucleon-Nucleon Collisions," Phys. Rev. **105** (1957) 1874–1899.

- [55] S. G. Mashnik, A. J. Sierk, O. Bersillon, and T. Gabriel, “Cascade-Exciton Model Detailed Analysis of Proton Spallation at Energies from 10 MeV to 5 GeV,” LANL Report LA-UR-97-2905 (1997), <http://t2.lanl.gov/publications/publications.html>.
- [56] C. H. M. Broeders and A. Yu. Konobeev, “Evaluation of He-4 Production Cross-Section for Tantalum, Tungsten and Gold Irradiated with Neutrons and Protons at the Energies up to 1 GeV,” Nucl. Instr. Meth. B **234** (2005) 387–411.
- [57] S. G. Mashnik, “Physics of the CEM92M Code,” pp. 107–120 in [10].
- [58] K. K. Gudima, S. G. Mashnik, and V. D. Toneev, “Preequilibrium Emission in Hadron-Nuclear Reactions at  $T_0 < 1\text{--}2$  GeV,” Proc. Europhysics Topical Conference June 21–25, 1982, Smollenice, Neutron Induced Reactions. Physics and Applications **10** (1982) 347–351.
- [59] V. D. Toneev and K. K. Gudima, “Particle Emission in Light and Heavy-Ion Reactions,” Nucl. Phys. **A400** (1983) 173c–190c.
- [60] K. K. Gudima, G. Röpke, H. Schulz, and V. D. Toneev, “The Coalescence Model and Pauli Quenching in High-Energy Heavy-Ion Collisions,” Joint Institute for Nuclear Research Preprint JINR-E2-83-101, Dubna (1983); H. Schulz, G. Röpke, K. K. Gudima, and V. D. Toneev, “The Coalescence Phenomenon and the Pauli Quenching in High-Energy Heavy-Ion Collisions,” Phys. Lett. B **124** (1983) 458–460.
- [61] Joseph I. Kapusta, “Mechanisms for Deuteron Production in Relativistic Nuclear Collisions,” Phys. Rev. C **21** (1980) 1301–1310.
- [62] Konstantin K. Gudima, Stepan G. Mashnik, and Arnold J. Sierk, “User Manual for the code LAQGSM,” LANL Report LA-UR-01-6804; <http://lib-www.lanl.gov/lapubs/00818645.pdf>.
- [63] N. S. Amelin, K. K. Gudima, and V. D. Toneev, “The Quark-Gluon String Model and Ultrarelativistic Heavy-Ion Collisions,” Yad. Fiz. **51** (1990) 512–523 [Sov. J. Nucl. Phys. **51** (1990) 327–333], N. S. Amelin, K. K. Gudima, and V. D. Toneev, “Further Development of the Model of Quark-Gluon Strings for the Description of High-Energy Collisions with a Target Nucleus,” Yad. Fiz. **52** (1990) 272–282 [Sov. J. Nucl. Phys. **52** (1990) 172–178].
- [64] T. Ericson, “The Statistical Model and Nuclear Level Densities,” Adv. in Physics **9** (1960) 425–511.
- [65] F. C. Williams Jr., “Intermediate State Transition Rates in the Griffin Model,” Phys. Lett. B **31** (1970) 184–186.
- [66] F. C. Williams Jr., Particle-Hole State Density in the Uniform Spacing Model,” Nucl. Phys. **A161** (1971) 231–240.
- [67] I. Ribansky, P. Oblozinsky, and E. Betak, “Pre-Equilibrium Decay and the Exciton Model,” Nucl. Phys. **A205** (1973) 545–560.
- [68] K. Kikuchi and M. Kawai, *Nuclear Matter and Nuclear Reactions*, North-Holland, Amsterdam (1968).

- [69] N. Metropolis, R. Bivins, M. Storm, A. Turkevich, J. M. Miller, and G. Friedlander, “Monte Carlo Calculations on Intranuclear Cascades. I. Low-Energy Studies,” *Phys. Rev.* **110** (1958) 185–203.
- [70] E. Betak, “Complex Particle Emission in the Exciton Model of Nuclear Reactions,” *Acta Phys. Slov.* **26** (1976) 21–24.
- [71] J. R. Wu and C. C. Chang, “Complex-Particle Emission in the Pre-Equilibrium Exciton Model,” *Phys. Rev. C* **17** (1978) 1540–1549.
- [72] G. Mantzouranis, H. A. Weidenmüller, and D. Agassi, “Generalized Exciton Model for the Description of Preequilibrium Angular Distributions,” *Z. Phys. A* **276** (1976) 145–154.
- [73] C. Kalbach, “Systematics of Continuum Angular Distributions: Extensions to Higher Energies,” *Phys. Rev.* **37** (1988) 2350–2370.
- [74] V. F. Weisskopf and D. H. Ewing, “On the Yield of Nuclear Reactions with Heavy Elements,” *Phys. Rev.* **57** (1940) 472–483.
- [75] N. Bohr and J. A. Wheeler, “The Mechanism of Nuclear Fission,” *Phys. Rev.* **56** (1939) 426–450.
- [76] A. V. Ignatyuk, G. N. Smirenkin, and A. S. Tishin, “Phenomenological Description of the Energy Dependence of the Level Density Parameter,” *Yad. Fiz.* **21** (1975) 485–490 [*Sov. J. Nucl. Phys.* **21** (1975) 255–257]; A. V. Ignatyuk, M. G. Itkis, V. N. Okolovich, G. N. Smirenkin, and A. S. Tishin, “Fission of Pre-Actinide Nuclei. Excitation Functions for the  $(\alpha, f)$  Reactions,” *Yad. Fiz.* **21** (1975) 1185–1205 [*Sov. J. Nucl. Phys.* **21** (1975) 612–621].
- [77] A. S. Iljinov, M. V. Mebel, N. Bianchi, E. De Sanctis, C. Guaraldo, V. Lucherini, V. Mucifora, E. Polli, A. R. Reolon, and P. Rossi, “Phenomenological Statistical Analysis of Level Densities, Decay Width and Lifetimes of Excited Nuclei,” *Nucl. Phys.* **A543** (1992) 517–557.
- [78] P. Möller, J. R. Nix, W. D. Myers, and W. J. Swiatecki, “Nuclear Ground-States Masses and Deformations,” *Atomic Data and Nuclear Data Tables*, **59** (1995) 185–381.
- [79] P. Möller, J. R. Nix, and K.-L. Kratz, “Nuclear Properties for Astrophysical and Radioactive-Ion-Beam Application,” *Atomic Data and Nuclear Data Tables*, **66** (1997) 131–343.
- [80] R. E. Prael and H. Lichtenstein, *User guide to LCS: The LAHET Code System*, LANL Report No. LA-UR-89-3014, Los Alamos (1989).
- [81] A. Ferrari, J. Ranft, S. Roesler, and P. R. Sala, “Cascade Particles, Nuclear Evaporation, and Residual Nuclei in High Energy Hadron-Nucleus Interactions,” *Z. Phys. C* **70** (1996) 413–426.
- [82] M. Veselský, “Production Mechanism of Hot Nuclei in Violent Collisions in the Fermi Energy Domain,” *Nucl Phys.* **A705** (2002) 193–222; M. Veselský, Š. Šáro, F. P. Heßberger, V. Ninov, S. Hofmann, and D. Ackermann, “Production of Fast Evaporation Residues by

- the Reaction  $^{20}\text{Ne} + ^{208}\text{Pb}$  at Projectile Energies of 8.6, 11.4 and 14.9 A MeV,” *Z. Phys. A* **356** (1997) 403–410.
- [83] M. Böhning, “Density of Particle-hole States in the Equidistant-Spacing Model,” *Nucl. Phys. A* **152** (1970) 529–546.
  - [84] S. Furihata, “Statistical Analysis of Light Fragment Production from Medium Energy Proton-Induced Reactions,” *Nucl. Instr. Meth. B* **171** (2000) 252–258; “The Gem Code—the Generalized Evaporation Model and the Fission Model,” *Proc. MC2000*, Lisbon, Portugal, 2000, edited by A. Kling, F. J. C. Barão, M. Nakagawa, L. Távora, and P. Vaz, Springer, Berlin, (2001), pp. 1045–1050; *The Gem Code Version 2 Users Manual*, Mitsubishi Research Institute, Inc., Tokyo, Japan (November 8, 2001).
  - [85] S. Furihata, K. Niita, S. Meigo, Y. Ikeda, and F. Maekawa, “The Gem Code—a Simulation Program for the Evaporation and Fission Process of an Excited Nucleus,” *JAERI-Data/Code* 2001-015, JAERI, Tokai-mura, Naka-gam, Ibaraki-ken, Japan (2001).
  - [86] Shiori Furihata, *Development of a Generalized Evaporation Model and Study of Residual Nuclei Production*, Ph.D. thesis, Tohoku University, March, 2003; S. Furihata and T. Nakamura, “Calculation of Nuclide Production from Proton Induced Reactions on Heavy Targets with INC/GEM,” *J. Nucl. Sci. Technol. Suppl.* **2** (2002) 758–761.
  - [87] I. Dostrovsky, Z. Frankel, and G. Friedlander, “Monte Carlo Calculations of Nuclear Evaporation Processes. III. Application to Low-Energy Reactions,” *Phys. Rev.* **116** (1959) 683–702.
  - [88] F. Atchison, “Spallation and Fission in Heavy Metal Nuclei under Medium Energy Proton Bombardment,” in *Proc. Meeting on Targets for Neutron Beam Spallation Source*, Julich, June 11–12, 1979, pp. 17–46, G. S. Bauer, Ed., *Jul-Conf-34*, Kernforschungsanlage Julich GmbH, Germany (1980).
  - [89] F. Atchison, “A Treatment of Fission for HETC,” in *Intermediate Energy Nuclear Data: Models and Codes*, pp. 199–218, *Proc. of a Specialists’s Meeting*, May 30–June 1, 1994, Issy-Les-Moulineaux, France, OECD, Paris, France (1994).
  - [90] G. Audi and A. H. Wapstra, “The 1995 Update to the Atomic Mass Evaluation,” *Nucl. Phys. A* **595** (1995) 409–480.
  - [91] P. E. Haustein, “An Overview of the 1986–1987 Atomic Mass Predictions,” *Atomic Data and Nuclear Data Tables* **39** (1988) 185–393.
  - [92] A. G. W. Cameron, “A Revised Semiempirical Atomic Mass Formula,” *Can. J. Phys.* **35** (1957) 1021–1032.
  - [93] T. Matsuse, A. Arima, and S. M. Lee, “Critical Distance in Fusion Reactions,” *Phys. Rev. C* **26** (1982) 2338–2341.
  - [94] A. S. Botvina, A. S. Iljinov, I. N. Mishustin, J. P. Bondorf, R. Donangelo, and K. Snappen, “Statistical Simulation of the Break-up of Highly Excited Nuclei,” *Nucl. Phys. A* **475** (1987) 663–686.

- [95] A. Gilbert and A. G. W. Cameron, “A Composite Nuclear-Level Density Formula with Shell Corrections,” *Can. J. Phys.* **43** (1965) 1446–1496.
- [96] J. L. Cook, H. Ferguson, and A. R. del Musgrove, “Nuclear Level Densities in Intermediate and Heavy Nuclei,” *Australian Journal of Physics* **20** (1967) 477–487.
- [97] W. A. Friedman and W. G. Lynch, “Statistical Formalism for Particle Emission,” *Phys. Rev. C* **28** (1983) 16–23.
- [98] The Evaluated Nuclear Structure Data File (ENSDF) maintained by the National Nuclear Data Center (NNDC), Brookhaven National Laboratory, <http://www.nndc.bnl.gov/>.
- [99] S. G. Mashnik, K. K. Gudima, R. E. Prael, and A. J. Sierk, “Analysis of the GSI A+p and A+A Spallation, Fission, and Fragmentation Measurements with the LANL CEM2k and LAQGSM Codes,” in *Proc. TRAMU@GSI, Darmstadt, Germany, 2003*, Eds. A. Kelic and K.-H. Schmidt, ISBN 3-00-012276-1, <http://ww-wnt.gsi.de/tramu>; E-print: nucl-th/0404018.
- [100] R. Vandenbosch and J. R. Huizenga, *Nuclear Fission*, Academic Press, New York (1973).
- [101] E. F. Neuzil and A. W. Fairhall, “Fission Product Yields in Helium Ion-Induced Fission of  $\text{Au}^{197}$ ,  $\text{Pb}^{204}$ , and  $\text{Pb}^{206}$  Targets,” *Phys. Rev.* **129** (1963) 2705–2710.
- [102] A. Ya. Rusanov, M. G. Itkis, and V. N. Okolovich, “Features of Mass Distributions of Hot Rotating Nuclei,” *Yad. Fiz.* **60** (1997) 773–803 [*Phys. At. Nucl.* **60** (1997) 683–712]; M. G. Itkis, Yu. A. Muzychka, Yu. Ts. Oganessian, V. N. Okolovich, V. V. Pashkevich, A. Ya. Rusanov, V. S. Salamatin, G. N. Smirenkin, and G. G. Chubaryan, “Fission of Excited Nuclei with  $Z^2/A=20\text{--}33$ : Mass-Energy Distributions of Fragments, Angular Momentum, and Liquid-Drop Model,” *Yad. Fiz.* **58** (1995) 2140–2165 [*Phys. At. Nucl.* **58** (1995) 2026–2051].
- [103] W. D. Myers and W. J. Swiatecki, “Thomas-Fermi Fission Barriers,” *Phys. Rev. C* **60** (1999) 014606.
- [104] M. G. Itkis, S. M. Luk’yanov, V. N. Okolovich, Yu. E. Penionzhkevich, A. Ya. Rusanov, V. S. Salamatin, G. N. Smirenkin, and G. G. Chubaryan, “Experimental Study of the Mass and Energy Distributions of Fragments from Fission,” *Ya. Fiz.* **52** (1990) 23–35 [*Sov. J. Nucl. Phys.* **52** (1990) 15–22].
- [105] F. Atchison, “A Revised Calculational Model for Fission,” Paul Scherrer Insitutut Report No. 98-12, Villigen PSI (1998).
- [106] H. W. Bertini, “Low-Energy Intranuclear Cascade Calculation,” *Phys. Rev.* **131** (1963) 1801–1871; “Intranuclear Cascade Calculation of the Secondary Nucleon Spectra from Nucleon-Nucleus Interactions in the Energy Range 340 to 2900 MeV and Comparison with Experiment,” *Phys. Rev.* **188** (1969) 1711–1730.
- [107] Y. Yariv and Z. Frankel, “Intranuclear Cascade Calculation of High-Energy Heavy-Ion Interactions,” *Phys. Rev. C* **20** (1979) 2227–2243; “Inclusive Cascade Calculation of High Energy Heavy Ion Collisions: Effect of Interactions between Cascade Particles,” *Phys. Rev. C* **24** (1981) 488–494.

- [108] A. V. Prokofiev, “Compilation and Systematics of Proton-Induced Fission Cross-Section Data,” Nucl. Instr. Meth. A **463** (2001) 557–575; A. V. Prokofiev, S. G. Mashnik, and W. B. Wilson, “Systematics of Proton-Induced Fission Cross Sections for Intermediate Energy Applications,” LANL Report LA-UR-02-5837, Los Alamos, 2002, E-print: nucl-th/0210071.
- [109] E. Fermi, “High Energy Nuclear Events”, Prog. Theor. Phys. **5** (1950) 570–583.
- [110] G. I. Kopylov, *Principles of Resonance Kinematics*, Moscow, Nauka (1970) [in Russian].
- [111] R. K. Tripathi, F. A. Cucinotta, and J. W. Wilson, “Accurate Universal Parameterization of Absorption Cross Sections,” Nucl. Instr. Meth. B **117** (1996) 347–349.
- [112] C. Kalbach, “Towards a Global Exciton Model; Lessons at 14 MeV,” J. Phys. G **24** (1998) 847–866.
- [113] M. V. Kossov, “Approximation of Photonuclear Interaction Cross-Sections,” Eur. Phys. J. A **14** (2002) 377–392.
- [114] K. Ukai and T. Nakamura, “Data Compilation of Single Pion Photoproduction Below 2 GeV”, INS-T-550, March 1997, Inst. for Nucl. Study, University of Tokyo, and private communication from K. Ukai to SGM (1997).
- [115] G. Roy, L. Greeniaus, G. A. Moss, D. A. Hutcheon, R. Liljestr nd, R. M. Woloshyn, D. H. Boal, A. W. Stetz, K. Aniol, A. Willis, N. Willis, and R. McCamis, “Inclusive Scattering of Protons on Helium, Nickel, and Tantalum at 500 MeV,” Phys. Rev. C **23** (1981) 16711–1678.
- [116] J. Ouyang, *Quasi-Free Pion Single Charge Exchange*, Ph.D. thesis U. of Colorado (LANL Report No. LA-12457-T, UC-413, 1992).
- [117] Melynda Louise Brooks, *Neutron Induced Pion Production on C, Al, Cu, and W at Neutron Energies of 200–600 MeV*, Ph.D. thesis, U. of New Mexico, (LA-12210-T, UC-910, Oct., 1991, Los Alamos); M. L. Brooks, B. Bassalleck, B. D. Dieterle, R. A. Reeder, D. M. Lee, J. A. McGill, M. E. Schillaci, R. A. Ristinen, and W. R. Smythe, “Neutron Induced Pion Production on C, Al, Cu, and W at 200–600 MeV,” Phys. Rev. C **45** (1992) 2343–2354.
- [118] T. Nakamoto, K. Ishibashi, N. Matsufuji, N. Shigyo, K. Maehata, H. Arima, S. Meigo, H. Takada, S. Chiba, and M. Numajiri, “Experimental Neutron-Production Double-Differential Cross Section for the Nuclear Reaction by 1.5 GeV  $\pi^+$  Mesons Incident on Iron,” J. Nucl. Sci. and Techn. **34** (1997) 860–862.
- [119] P. Staples, N. W. Hill, and P. W. Lisowski, “Fission Cross Section Ratios of  $^{nat}\text{Pb}$  and  $^{209}\text{Bi}$  Relative to  $^{235}\text{U}$  for Neutron Energies from Threshold to 400 MeV,” Bull. Am. Phys. Soc., **40** (1995) 962; Parrish Staples and Kevin Morley, “Neutron-Induced Fission Cross-Section Reactions for  $^{239}\text{Pu}$ ,  $^{240}\text{Pu}$ ,  $^{242}\text{Pu}$ , and  $^{244}\text{Pu}$  Relative to  $^{235}\text{U}$  from 0.5 to 400 MeV,” Nucl. Sci. Eng. **129** (1998) 149–163, and private communication from P. Staples to T-2, LANL, 1996.

- [120] A. V. Prokofiev, P.-U. Renberg, and N. Olson, “Measurement of Neutron-Induced Fission Cross Sections for  $^{nat}\text{Pb}$ ,  $^{208}\text{Pb}$ ,  $^{197}\text{Au}$ ,  $^{nat}\text{W}$ , and  $^{181}\text{Ta}$  in the Intermediate Energy Region,” Uppsala University Neutron Physics Report UU-NF 01#6 (March 2001).
- [121] A. N. Smirnov, V. P. Eismont, N. P. Filatov, J. Blumgren, H. Condé, A. V. Prokofiev, P.-U. Renberg, and N. Olsson, “Measurements of Neutron-Induced Fission Cross Sections for  $^{209}\text{Bi}$ ,  $^{nat}\text{Pb}$ ,  $^{208}\text{Pb}$ ,  $^{197}\text{Au}$ ,  $^{nat}\text{W}$ , and  $^{181}\text{Ta}$  in the Intermediate Energy Region,” *Phys. Rev. C* **70** (2004) 054603.
- [122] A. Guertin, N. Marie, S. Auduc, V. Blideanu, Th. Delbar, P. Eudes, Y. Foucher, F. Haddad, T. Kirchner, Ch. Le Brun, C. Lebrun, F. R. Lecolley, J. F. Lecolley, X. Ledoux, F. Lefèbvres, T. Lefort, M. Louvel, A. Ninane, Y. Patin, Ph. Pras, G. Rivière, and C. Varignon, “Neutron and Light-Charged-Particle Productions in Proton-Induced Reactions on  $^{208}\text{Pb}$  at 62.9 MeV,” *Eur. Phys. J.* **A23** (2005) 49–60.
- [123] F. Rejmund, B. Mustapha, P. Armbruster, J. Benlliure, M. Bernas, A. Boudard, J. P. Dufour, T. Enqvist, R. Legrain, S. Leray, K.-H. Schmidt, C. Stéphan, J. Taieb, L. Tassan-Got, and C. Volant, “Measurement of Isotopic Cross Sections of Spallation Residues in 800 A MeV  $^{197}\text{Au} + \text{p}$  Collisions,” *Nucl. Phys.* **A683** (2001) 540–565; J. Benlliure, P. Armbruster, M. Bernas, A. Boudard, J. P. Dufour, T. Enqvist, R. Legrain, S. Leray, B. Mustapha, F. Rejmund, K.-H. Schmidt, C. Stéphan, L. Tassan-Got, and C. Volant, “Isotopic Production Cross Sections of Fission Residues in  $^{197}\text{Au}$ -on-Proton Collisions at 800 A MeV,” *Nucl. Phys.* **A683** (2001) 513–539.
- [124] Carmen Villagrasa-Canton, “Etude de la production des noyaux résiduels dans la réaction de spallation  $\text{Fe} + \text{p}$  à 5 énergies (300–1500 MeV/A) et application au calcul de dommage sur une fenêtre de système hybride,” PhD Thesis, Université de Paris XI Orsay, December 5, 2003, <http://www-w2k.gsi.de/charms/theses.htm>, and private communication from Dr. Villagrasa to SGM, March 11, 2004.
- [125] Paolo Napolitani, “New Findings on the Onset of Thermal Disassembly in Spallation Reactions,” PhD Thesis, University Paris XI Orsay, IPNO-T-04-14, September 24, 2004; P. Napolitani, K.-H. Schmidt, A. S. Botvina, F. Rejmund, L. Tassan-Got, and C. Villagrasa, “High-Resolution Velocity Measurements on Fully Identified Light Nuclides Produced in  $^{56}\text{Fe} + \text{Hydrogen}$  and  $^{56}\text{Fe} + \text{Titanium}$  Systems,” *Phys. Rev. C* **70** (2004) 054607.
- [126] R. A. Schumacher, G. S. Adams, D. R. Ingham, J. L. Matthews, W. W. Sapp, R. S. Turley, R. O. Owens, and B. L. Roberts, “ $\text{Cu}(\gamma, p)\text{X}$  Reaction at  $E_\gamma = 150$  and 300 MeV,” *Phys. Rev. C* **25** (1982) 2269–2277.
- [127] Koh Sakamoto, “Radiochemical Study on Photonuclear Reactions of Complex Nuclei at Intermediate Energies,” *J. Nucl. Radiochem. Sci.* **4** (2003) A9–A31.