MERGING THE CEM2K AND LAQGSM CODES WITH GEM2 TO DESCRIBE FISSION AND LIGHT-FRAGMENT PRODUCTION

S. G. Mashnik\textsuperscript{1}, K. K. Gudima\textsuperscript{2}, and A. J. Sierk\textsuperscript{1}

\textsuperscript{1}Los Alamos National Laboratory, Los Alamos, NM 87545, USA

\textsuperscript{2}Institute of Applied Physics, Academy of Science of Moldova, Kishinev, MD-2028, Moldova

Abstract

We present the current status of the improved Cascade-Exciton Model (CEM) code CEM2k and of the Los Alamos version of the Quark-Gluon String Model code LAQGSM. To describe fission and light-fragment (heavier than He4) production, both CEM2k and LAQGSM have been merged with the GEM2 code of Furihata. We present some results on proton- and deuteron-induced spallation, fission, and fragmentation reactions predicted by these extended versions of CEM2k and LAQGSM. We show that merging CEM2k and LAQGSM with GEM2 allows us to describe many fission and fragmentation reactions in addition to the spallation reactions which are already relatively well described. Nevertheless, the standard version of GEM2 does not provide a completely satisfactory description of complex particle spectra, heavy-fragment emission, and spallation yields, and is not yet a reliable tool for applications. We conclude that we may choose to use a model similar to the GEM2 approach in our codes, but it must be significantly extended and further improved. We observe that it is not sufficient to analyze only A and Z distributions of the product yields when evaluating this type of model, as is often done in the literature; instead it is important to study all the separate isotopic yields as well as the spectra of light particles and fragments.
Introduction

During recent years, for a number of applications like Accelerator Transmutation of nuclear Wastes (ATW), Accelerator Production of Tritium (APT), Rare Isotope Accelerator (RIA), Proton Radiography (PRAD), and others projects, we have developed at the Los Alamos National Laboratory an improved version of the Cascade-Exciton Model (CEM), contained in the code CEM2k, to describe nucleon-induced reactions at incident energies up to 5 GeV [1] and the Los Alamos version of the Quark-Gluon String Model, realized in the high-energy code LAQGSM [2], able to describe both particle- and nucleus-induced reactions at energies up to about 1 TeV/nucleon.

In our original motivation, different versions of the CEM and LAQGSM codes were developed to reliably describe the yields of spallation products and spectra of secondary particles, without a special emphasis on complex-particle and light-fragment emission or on fission fragments in reactions with heavy targets. In fact, the initial versions of the CEM2k and LAQGSM codes simulate spallation only and do not calculate the process of fission, and do not provide fission fragments and a further possible evaporation of particles from them. Thus, in simulating the compound stage of a reaction, when these codes encounter a fission, they simply tabulate this event (that permits calculation of fission cross sections and fissility) and finish the calculation of this event without a subsequent treatment of fission fragments. To be able to describe nuclide production in the fission region, these codes have to be extended by incorporating a model of high energy fission (e.g., in the transport code MCNPX [3], where CEM2k and, initially, its precursor, CEM97 [4], are used, they are supplemented by Atchison’s fission model [5, 6].

Since many nuclear and astrophysical applications require reliable data also on complex particles (gas production) and light and/or fission fragment production, we addressed these questions by further development of CEM2k and LAQGSM codes. We tried different ways of solving these problems and as a first attempt to describe with our codes both emission of intermediate-mass fragments heavier than $^4$He and production of heavy fragments from fission, we merged CEM2k and LAQGSM with the Generalized Evaporation Model (GEM) code by Furihata [7, 8]. We have benchmarked our codes on all proton-nucleus and nucleus-nucleus reactions measured recently at GSI (Darmstadt, Germany) and on many other different reactions at lower and higher energies measured earlier at other laboratories. The size of the present paper allows us to present here only a few results, which we choose to be for the GSI measurements on interaction of $^{208}$Pb beams with p [9] and d [10] targets. Results for other reactions may be found in [11, 12].

CEM2k and LAQGSM Codes

A detailed description of the initial version of the CEM may be found in Ref. [13], therefore we outline here only its basic assumptions. The CEM assumes that reactions occur 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. The excited residual nucleus remaining after
the cascade determines the particle-hole configuration that is the starting point for the preequilibrium stage of the reaction. The subsequent relaxation of the nuclear excitation is treated in terms of an improved Modified Exciton Model (MEM) of preequilibrium decay followed by the equilibrium evaporative final stage of the reaction. Generally, all three stages contribute to experimentally measured outcomes.

The improved cascade-exciton model in the code CEM2k differs from the older CEM95 version (which is available free from the NEA/OECD, Paris) by incorporating new approximations for the elementary cross sections used in the cascade, using more precise values for nuclear masses and pairing energies, employing a corrected systematics for the level-density parameters, adjusting the cross sections for pion absorption on quasi-deuteron pairs inside a nucleus, including the Pauli principle in the preequilibrium calculation, and improving the calculation of the fission widths. Implementation of significant refinements and improvements in the algorithms of many subroutines led to a decrease of the computing time by up to a factor of 6 for heavy nuclei, which is very important when performing simulations with transport codes. Essentially, CEM2k has a longer cascade stage, less preequilibrium emission, and a longer evaporation stage with a higher excitation energy, as compared to its precursors CEM97 and CEM95. Besides the changes to CEM97 and CEM95 mentioned above, we also made a number of other improvements and refinements, such as: (i) imposing momentum-energy conservation for each simulated event (the Monte Carlo algorithm previously used in CEM provides momentum-energy conservation only statistically, on the average, but not exactly for the cascade stage of each event), (ii) using real binding energies for nucleons at the cascade stage instead of the approximation of a constant separation energy of 7 MeV used in previous versions of the CEM, (iii) using reduced masses of particles in the calculation of their emission widths instead of using the approximation of no recoil used previously, and (iv) a better approximation of the total reaction cross sections. On the whole, this set of improvements leads to a much better description of particle spectra and yields of residual nuclei and a better agreement with available data for a variety of reactions. Details, examples, and further references may be found in Refs. 1, 15.

The Los Alamos version of the Quark-Gluon String Model (LAQGSM) is the next generation of the Quark-Gluon String Model (QGSM) by Amelin et al. (see references therein) and is intended to describe both particle- and nucleus-induced reactions at energies up to about 1 TeV/nucleon. The core of the QGSM is built on a time-dependent version of the intranuclear cascade model developed at Dubna, often referred in the literature simply as the Dubna intranuclear Cascade Model (DCM) (see references therein). The DCM models interactions of fast cascade particles (“participants”) with nucleon spectators of both the target and projectile nuclei and includes interactions of two participants (cascade particles) as well. It uses experimental cross sections (or those calculated by the Quark-Gluon String Model for energies above 4.5 GeV/nucleon) for these elementary interactions to simulate angular and energy distributions of cascade particles, also considering the Pauli exclusion principle. When the cascade stage of a reaction is completed, QGSM uses the coalescence model described in to “create” high-energy d, t, 3He, and 4He by final state interactions among emitted cascade nucleons, already outside of the colliding nuclei. After calculating the coalescence stage of a reaction, QGSM
moves to the description of the last slow stages of the interaction, namely to preequilibration decay and evaporation, with a possible competition of fission using the standard version of the CEM. But if the residual nuclei have atomic numbers with \( A \leq 13 \), QGSM uses the Fermi break-up model to calculate their further disintegration instead of using the preequilibrium and evaporation models. LAQGSM differs from QGSM by replacing the preequilibrium and evaporation parts of QGSM described according to the standard CEM with the new physics from CEM2k and has a number of improvements and refinements in the cascade and Fermi break-up models (in the current version of LAQGSM, we use the Fermi break-up model only for \( A \leq 12 \)). A detailed description of LAQGSM and further references may be found in [2].

We have benchmarked CEM2k and LAQGSM against most available experimental data and have compared our results with predictions of other current models used by the nuclear community. Figure 1 shows examples of calculated neutron spectra from the interaction of protons with \(^{208}\)Pb at 0.8 and 1.5 GeV compared with experimental data, while Figure 2 gives examples of neutron spectra measured by Nakamura’s group (see references therein) from 560 MeV/nucleon Ar beams on C, Cu, and Pb targets compared with our LAQGSM results and predictions by QMD and HIC from Iwata et al. We see that our codes describe well neutron spectra both for proton- and nucleus-nucleus reactions and agree with the data no worse than other models do. Similar results are obtained for other reactions for which we found measured data.

**Merging CEM2k and LAQGSM with GEM2**

The Generalized Evaporation Model (GEM) is an extension by Furihata of the Dostrovsky et al. evaporation model as implemented in LAHET 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 used in LAHET. Many of the parameters were adjusted for a better description of fission reactions when using it in conjunction with the extended evaporation model. We merged GEM2 (the last update of the GEM code) with CEM2k and LAQGSM as follows: we calculate the cascade and preequilibrium stages of a reaction with our CEM2k or LAQGSM, then we describe the subsequent evaporation of particles and fragments and fission from the remaining excited compound nuclei using GEM2. To understand the role of preequilibrium particle emission, we performed calculations of all the reactions we tested both with emission of preequilibrium particles and without them, i.e., going directly to GEM2 after the intranuclear cascade stage of a reaction described by CEM2k or LAQGSM.

A very detailed description of the GEM, together with a large amount of results obtained for many reactions using GEM coupled either with the Bertini or ISABEL INC models in LAHET are published by Furihata; many useful details of GEM2 may be found also in our paper. Therefore, we list briefly below only the main features of GEM and forward readers interested in details to Refs. Furihata did not change in 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 theory.
Figure 1. Comparison of measured double differential cross sections of neutrons from 0.8 and 1.5 GeV protons on Pb with CEM2k and LAQGSM calculations.
Figure 2. Comparison of measured \[19\] double differential cross sections of neutrons from 560 MeV/nucleon Ar beams on C, Cu and Pb with our LAQGSM results and calculations by QMD \[20\] and HIC \[21\] from Iwata et al. \[19\].
The new ingredient in GEM in comparison with LAHET which considers evaporation of only 6 particles (n, p, d, t, \(^{3}\)He, and \(^{4}\)He) is that Furihata included the possibility of evaporation of up to 66 types of particles and fragments (both in the ground and excited states) and incorporated into GEM several sets of parameters used to calculate inverse cross sections and Coulomb barriers for each ejectile (we use here only default parameters of GEM2). The 66 ejectiles considered by GEM are: n, p, d, t, \(^{3}\)He, and \(^{4}\)He, \(^{6}\)Li, \(^{7}\)Li, \(^{10}\)Be, \(^{12}\)C, \(^{14}\)O, \(^{17}\)F, \(^{19}\)F, \(^{21}\)Na, and \(^{22}\)Mg.

The fission model used in GEM is based on Atchison’s model [5, 6] as implemented in LAHET [23], often referred in the literature as the Rutherford Appleton Laboratory (RAL) model, which is where Atchison developed it. There are two choices of parameters for the fission model: one of them is the original parameter set by Atchison [5, 6] as implemented in LAHET [23], and the other is a parameter set evaluated by Furihata [7, 8], used here as a default of GEM2.

The Atchison fission model is designed to only describe 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, \(^{3}\)He, and \(^{4}\)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 [6]) 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 about \(Z^2/A \approx 34\) would more sensible [11].

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

\[
P_f = \frac{\Gamma_f}{\Gamma_f + \Gamma_n} = \frac{1}{1 + \Gamma_n/\Gamma_f}.
\]

Atchison uses [5, 6] the Weisskopf and Ewing statistical model [25] with an energy-independent pre-exponential factor for the level density (see Eq. (6) in [11]) and Dostrovsky’s [22] inverse cross section for neutrons and estimates the neutron width \(\Gamma_n\) as

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

where \(J_0\) and \(J_1\) are functions of the level density parameter \(a_n\) and \(s_n\) as

\[
J_0 = \frac{(s_n - 1)e^{s_n} + 1}{2a_n} \quad \text{and} \quad J_1 = \frac{(2s_n^2 - 6s_n + 6)e^{s_n} + s_n^2 - 6}{8a_n^2}.
\]

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

\[
a_n = (A_i - 1)/8,
\]
and this approximation is kept in GEM when calculating the fission probability according to Eq. (1), though it differs from the Gilbert-Cameron-Cook-Iginyuk (GCCI) parameterization (see Eq. (7) in [11]) used in GEM 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 GEM as

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

(4)

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 [6] to describe the measured $\Gamma_f/\Gamma_n$ as:

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

(5)

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

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

(6)

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

2) $Z_j \geq 89$. For heavy fissioning nuclei with $Z_j \geq 89$ GEM follows the RAL model [5, 6] and does not calculate at all the fission width $\Gamma_f$ and does not use Eq. (1) to estimate the fission probability $P_f$. Instead, the following semi-empirical expression obtained by Atchison [5, 6] by approximating the experimental values of $\Gamma_n/\Gamma_f$ published by Vandenbosch and Huizenga [26] is used to calculate the fission probability:

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

(7)

where $C(Z)$ and $A_0(Z)$ are constants dependent on the nuclear charge $Z$ only. The values of these constants are those used in the current version of LAHE T [23] and are tabulated in Table 5 of Ref. [11] (note that some adjustments of these values have been done since Atchison’s papers [5, 6] were published).

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 $E$ of the fissioning nucleus. No new parameters were determined for asymmetric fission in GEM.

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

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

(8)

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 $A_2 = A_i - A_1$. 

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 in [7, 8, 11].

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

\[
Z_f = \frac{Z_i + Z_i' - Z_2}{2}, \quad \text{where} \quad Z_i' = \frac{65.5A_i}{131 + A_i^{2/3}}, \quad \text{and} \quad l = 1 \text{ or } 2.
\]

The original Atchison model uses \( \sigma_Z = 2.0 \). An investigation by Furihata [8] suggests that \( \sigma_Z = 0.75 \) provides a better agreement with data; therefore \( \sigma_Z = 0.75 \) is used in GEM2 and in all our calculations.

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:

\[
\epsilon_f = 0.133Z_i^2/A_i^{1/3} - 11.4, \quad \text{and} \quad \sigma_{\epsilon_f} = 0.084\epsilon_f.
\]

Furihata’s parameters in GEM2, which we also use, are:

\[
\epsilon_f = \begin{cases} 
0.131Z_i^2/A_i^{1/3}, & \text{for } Z_i^2/A_i^{1/3} \leq 900, \\
0.104Z_i^2/A_i^{1/3} + 24.3, & \text{for } 900 < Z_i^2/A_i^{1/3} \leq 1800,
\end{cases}
\]

and

\[
\sigma_{\epsilon_f} = \begin{cases} 
C_1(Z_i^2/A_i^{1/3} - 1000) + C_2, & \text{for } Z_i^2/A_i^{1/3} > 1000, \\
C_2, & \text{for } Z_i^2/A_i^{1/3} \leq 1000,
\end{cases}
\]

where \( C_1 = 5.70 \times 10^{-4} \) and \( C_2 = 86.5 \). More details may be found in [8].

We note that Atchison also has modified his original version using recent data and published [27] an improved (and more complicated) parameterization for many quantities and distributions in his model, but these modifications [27] are not yet included either in LAHET or in GEM2.

We have merged the GEM2 code with our CEM2k and LAQGSM, initially keeping all the default options in GEM2. We began by concentrating on an analysis of the recent GSI measurements in inverse kinematics as the richest and best data set for testing this kind of model. As mentioned above, to understand the role of preequilibrium particle emission, we performed calculations of all the reactions we tested both taking into account preequilibrium particle emission and ignoring it, \( i.e. \), going directly to GEM2 after the intranuclear cascade stage of a reaction described by CEM2k or LAQGSM.

If we merge GEM2 with CEM2k without any modifications, the new code does not describe correctly the fission cross section (and the yields of fission fragments) whether we take into account preequilibrium emission (see the short-dashed line on Fig. 3) or not (see the long-dashed line on Fig. 3). Such results were anticipated, as Atchison fitted the parameters of his RAL fission model when it was coupled with the Bertini INC [28] which differs from our INC. In addition, he 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.
Figure 3. Comparison of the experimental mass and charge distributions of the nuclides produced in the reaction $p(1 \text{ GeV}) + ^{208}\text{Pb}$ (circles show data from Tabs. 3 and 4 of Ref. [9] and squares - from Fig. 13 of Ref. [10]) with different calculations. The dashed lines show results found by merging CEM2k with GEM2 without any modifications when preequilibrium emission is (thin lines) or is not (thick lines) included. Solid lines show results from CEM2k+GEM2 with a modified $a_f$: thin lines are for the case with preequilibrium emission ($a_{f}^{CEM}/a_{f}^{RAL} = 1.06$) and thick lines show the results without preequilibrium emission ($a_{f}^{CEM}/a_{f}^{RAL} = 0.947$).
Furihata used GEM2 coupled either with the Bertini INC [28] or with the ISABEL [29] INC code, which also differs from our INC, and did not include preequilibrium particle emission. Therefore the real fissioning nuclei simulated by Furihata differ from the ones in our simulations, and the parameters adjusted by Furihata to work the best with her INC should not be the best for us. To get a good description of the fission cross section (and fission-fragment yields) we need to modify at least one parameter in GEM2, namely to adjust the level density parameter $a_f$ to get the correct fission cross section (see Eq. (5)), in the case of fissioning nuclei with $Z \leq 88$ (pre-actinides), and the parameter $C(Z)$ (see Eq. (7)) for fissioning nuclei with $Z > 88$ (actinides). From the dashed lines on Fig. 5 we see that we need to enlarge $a_f$ in our code to get a proper fission cross section when we include preequilibrium emission (the excitation energy of our fissioning nuclei and their $A$ and $Z$ are smaller than provided by the Bertini or ISABEL INC without preequilibrium), and we need to decrease $a_f$ in the case without preequilibrium. By increasing $a_f$ by 1.06 compared with the original RAL and GEM2 value ($a_f^{CEM}/a_f^{RAL} = 1.06$), we are able to reproduce correctly with CEM2k+GEM2 the fission cross section for this reaction when we take into account preequilibrium emission (below, we label such results as “with Prec”). In the case with no preequilibrium emission, a proper fission cross section is obtained for $a_f^{CEM}/a_f^{RAL} = 0.947$ (we label such results as “no Prec”). We choose these values for $a_f$ for all our further CEM2k+GEM2 calculations of this reaction and do not change any other parameters.

The solid lines in Fig. 3 show results with these values of $a_f$. One can see that the “no Prec” version provide a good description of both the mass and charge distributions and agrees better with the data for these characteristics than the “with Prec” version (that is not true for isotopic distributions of individual elements, as we show below). The “with Prec” version reproduces correctly the position of the maximum in both $A$ and $Z$ distributions and the yields of fission fragments not too far from these maximums, but the calculated distributions are narrower than the experimental ones. This is again because both Atchison and Furihata fitted their $A$ and $Z$ distributions using models without preequilibrium emission, which provide higher values for the excitation energy, $A$, and $Z$ of fissioning nuclei. This means that to get a good description of $A$ and $Z$ distributions for fission fragments using GEM2 in CEM2k “with Prec”, we would need to modify the $A$ and $Z$ distributions of fission fragments in GEM2, making them wider. This would take us beyond the scope of the present work and here we do not vary any more parameters than we have already discussed.

Fig. 4 shows the GSI measurements [9] of the $A$ and $Z$ distributions of the kinetic energy of products from the same reaction compared with our CEM2k+GEM2 calculations both with and without preequilibrium emission. Both versions of our calculations are in reasonable agreement with the data.

Mass and charge distributions of the yields or kinetic energies of the nuclides produced show only general trends and are not sensitive enough to the details of a reaction. It is much more informative to study the characteristics of individual nuclides and particles produced in a reaction. Fig. 5 shows a comparison of the experimental data on production yields of thirteen separate isotopes with $Z$ lying from 22 to 82 from the same reaction measured at GSI [9] with our calculations using both the “with Prec” (upper plot) and
Figure 4. Comparison of the experimental mass and charge distributions of the spallation-residue kinetic energies of the nuclides produced in the reaction p(1 GeV) + Pb (circles) with our CEM2k+GEM2 calculations: “with Prec” results are shown by solid lines, “no Prec” results are shown by dashed lines.

“no Prec” (middle plot) versions.

The agreement (or disagreement) of our calculations with these data is different from what we have for the integral A or Z distributions in Figs. 3 and 4: We see that for the isotopes produced in the spallation region (not too far from the target) and for fission fragments in the region with the maximum yield, the version “with Prec” agree much better with the data than the version “no Prec”. Only for production of isotopes at the border between spallation and fission and between fission and fragmentation does the version “with Prec” underestimates the data, due to too narrow A and Z distributions in the simulation of fission fragments, as we discussed previously. The “no Prec” version agrees better with the data in these transition regions but are in worse agreement for isotopes both in the spallation region and in the middle of the fission region. We conclude that if a model agrees well with some A or Z distributions it does not necessarily mean that it also describes well production of separate isotopes. In other words, integral A and Z distributions are not sensitive enough to develop and test such models, a practice which is often used in the literature.

The lower plot in Fig. 5 shows results of calculations with a version of CEM2k+GEM2 with reduced preequilibrium emission. We prefer to discuss this version together with results by LAQGSM+GEM2, and will return to this plot later.

It is more difficult for any model to describe correctly the energy dependence for the production cross sections of different isotopes, i.e., excitation functions. We calculated using both the “with Prec” and “no Prec” versions of CEM2k+GEM2 all the excitation functions for the same reaction, p + Pb, for proton energies from 10 MeV to 3 GeV and compared our results with all available data from our compilation referred to here as T-16 Library (“T16 Lib”) [30]. Only several typical examples from our comparison are shown below.

Fig. 6 shows two examples of excitation functions for the production of several isotopes in the spallation (first two columns of plots) and fission (the last two columns of plots).
Figure 5. Experimental [9] mass distributions of the cross sections of thirteen isotopes with the charge $Z$ from 22 to 82 compared with our CEM2k+GEM2 calculations. “With Prec” results are shown on the upper plot, “no Prec” results are shown in the middle, while results with reduced preequilibrium emission according to Eq. (9), in the lower one.
One can see a not too good but still reasonable agreement of both calculations with many data (note that most of the data were measured for nat Pb targets, while our calculations were done for 208 Pb). We see that merging CEM2k with GEM2 allows us to reasonably describe yields of fission fragments, while in the old standard CEM2k we do not have any fission fragments and are unable to describe such reactions at all. We see that as shown in Fig. 5 for a single proton energy of 1 GeV, the “with Prec” version agrees better with the data in the whole energy region both for spallation products and for the production of most of the fission fragments. Only on the border between fission and fragmentation regions (46 Sc and 60 Co) does the “no Prec” version agree much better with the data than the “with Prec” version; the reason for this we have already discussed. Similar results were obtained for excitation functions of many other isotopes in the spallation and fission regions. On the whole, the version “with Prec” reproduces most of the experimental excitation functions better that the version “no Prec”.

In Fig. 7 we show examples of excitation functions for the production of light fragments (the first two columns of plots), in the fragmentation region, that are produced in CEM2k+GEM2 only via evaporation (the contribution to the yield of these isotopes from fission or deep spallation is negligible), and of nucleons and complex particles up to α (the last two columns of plots). We see that with the “no Prec” version, GEM2 reproduces correctly the yields of light fragments 4 He, 9 Li, 7 Be, 13 N, and 18 F, and not so well the excitation functions for heavier fragments like 22 Na. With increasing mass of the fragment, the calculations progressively underestimate their yields. Note, that in [30], we got very similar results for excitation functions for the p+Au reaction. The version
“with Prec” strongly underestimates the yields of all these fragments, and this is again not surprising, as Furihata developed her model and fitted all parameters without taking into account pre-equilibrium processes.

Undeniably, the parameters determining the yields of evaporated fragments in GEM (inverse cross sections and Coulomb barriers) could be adjusted to get a good agreement with the data for the yields of light fragments with the version “with Prec” (see, e.g., how Furihata and Nakamura addressed this problem in [24] for their version of a code without pre-equilibrium emission). This is not the aim of our present work and we will not do this here. Even if we were to do this, we expect in advance to get similar results to those we got for the “no Prec” version: It would be possible to describe correctly the yields and spectra of light fragments but not of heavy fragments like \(^{24}\text{Na}\) and \(^{28}\text{Mg}\). To describe such heavy fragments (not only their yields, but also their spectra) the model would need to be improved further, by considering other mechanisms for heavy fragment production in addition to the evaporation process taken into account by GEM2.

Finally, the two last columns of plots in Fig. 7 show excitation functions for emission of nucleons and complex particles up to \(\alpha\) for this reaction. Note that the data for these excitation functions are not so extensive and precise as we have for heavier products: many data points were obtained by integration (plus extrapolation) of the spectra of particles measured only at several angles and only for a limited range of energy. But even from a comparison with these sparse and imprecise data we see that the “with Prec” version describes these excitation function better than the “no Prec” version, just as we found in [11] for the p+Au reaction. This is an expected result as the high Coulomb barriers
for heavy nuclear targets oppose evaporation of low energy charged particles and the main contribution to their yields comes from preequilibrium emission from highly excited pre-compound nuclei.

For completeness sake, we show here also an example of results from a calculation with the merged CEM2k+GEM2 code of a reaction on an actinide, p(100 MeV) + $^{238}$U. Generally, to get for actinides a proper fission cross section, we need to adjust in GEM2 the parameters $C(Z)$ (or, also $A_0(Z)$) in Eq. (7), as they were fitted by Atchison to work the best with Bertini’s INC and we have in CEM2k our own INC. As mentioned above, for actinides, Eq. (1) is not used in GEM2 and $a_f$ is not used in any calculations, therefore we do not need to adjust $a_f/a_n$, for fissioning nuclei with $Z > 88$. We found that for this particular reaction, p(100 MeV) + $^{238}$U, we get with CEM2k+GEM2 a fission cross section in agreement with the data without any adjustments of the parameter $C(Z)$ in GEM2, i.e., we can use just the default parameters of GEM2. Nevertheless, our results for other reactions show that for higher energies of the incident protons or for other target-nuclei, the parameter $C(Z)$ has to be fitted to get a correct fission cross section when GEM2 is coupled either with CEM2k or with LAQGSM. In addition, we should mention that for reactions on actinides at intermediate or high energies, the parameter $a_f^{CEM}/a_f^{RAL}$ should also be fitted along with $C(Z)$. In some simulated events several protons can be emitted at the cascade and preequilibrium stages of the reaction, as well as at the evaporation stage, before the compound nucleus actually fissions (also complex particles can be emitted before fission), and the charge of the fissioning nucleus can have $Z \leq 88$, even when the initial charge of the target has $Z > 88$. At the same time, for $Z \leq 88$, due to charge exchange reactions, the charge of the fissioning nucleus may exceed 88, so that we would need to fit as well $C(Z)^{CEM}/C(Z)^{RAL}$. This is a peculiarity of treating the fission probability $P_f$ differently for the elements above and below $Z = 89$ in the Atchison model.

Fig. 8 shows mass distributions of products from p(100 MeV) + $^{238}$U calculated with both versions of CEM2k+GEM2 compared to the available experimental data [32] and with results by the phenomenological code CYF of Wahl [33] (short dashed lines). We need to mention that these data are not as good for testing and developing models as are the GSI data measured in inverse kinematics for the p + Pb reaction discussed above: All the data shown in Fig. 8 were obtained by the $\gamma$-spectrometry method. Only some of the produced isotopes were measured, and most of the data were measured for the cumulative yields. To get the “experimental” A-distribution, we summed for each $A$ the available data taking care to not sum the individual cross sections already included in some cumulative yields; but the resulting A-distribution is still not complete, as many isotopes were not measured. This means that some theoretical values can be above the experimental data (where some isotopes were not measured) without necessarily implying disagreement between calculations and measurements.

One can see that both the “with Prec” and “no Prec” versions of CEM2k+GEM2 describe equally well the mass distribution of the products from this reaction; therefore it is not possible to choose between either of the versions from a comparison with these not very informative data. We see that results by the phenomenological code CYF of Wahl [33] also agree well with the A-distribution of measured fission products. It is more
Figure 8. Comparison of the experimental[32] mass distribution of the nuclides produced in the reaction $p(100\text{ MeV}) + ^{238}\text{U}$ (circles) with calculations by the CEM2k+GEM2 model when pre-equilibrium emission is (solid lines) or is not (long dashed lines) included and with results by the phenomenological code CYF of Wahl[33] (short dashed lines). Note that measurements were done on natU while calculations were performed for $^{238}\text{U}$.

useful to compare calculations with the yields of individually measured isotopes. In Fig. 9, we compare our calculations with all cross sections measured by Titarenko[32] for each nuclide separately, where we can compare our results with the data (we do not include in our comparison the nuclides measured only either in their isomer or ground states, as our model does not provide such information: CEM2k+GEM2 provides only yields for the sum of isotope production cross sections both in their ground and excited states). We see that on the whole, the “with Prec” version agrees better with most of the individually measured cross sections than the “no Prec” version and for many of the measured isotopes the disagreement is less than a factor of two, with several of our calculated points coinciding with the data within the plotting accuracy. Nevertheless, for several isotopes like $^{72}\text{Ga}$, $^{227}\text{Th}$, $^{228}\text{Pa}$, and $^{238}\text{Np}$, we see some big disagreements. For comparison, we also show in Fig. 9 calculations by the phenomenological code YIELDX of Silberberg, Tsao, and Barghouty[34] and using its 2000 updated version, YIELDX2k[35], and with the phenomenological code CYF by Wahl[65] often used in applications. We see that these phenomenological systematics fail to describe the production of many isotopes from this reaction, indicating that we cannot rely on phenomenological systematics and must develop reliable models to be used in applications.

Very similar results for the studied proton-induced reactions with the ones shown above by CEM2k+GEM2 were obtained also by merging LAQGSM with GEM2. We
Figure 9. Detailed comparison between experimental \[32\] (filled squares) and calculated cross sections of all individual and cumulative (labeled with a “c”) products measured for the reaction $p(100 \text{ MeV}) + ^{238}\text{U}$ Our CEM2k+GEM2 “with Prec” results are shown by connected opaque squares and the “no Prec” results are shown by connected circles. Predictions by the phenomenological code CYF \[33\] are shown with connected diamonds, and results calculated by the phenomenological systematics YIELDX \[34\] are shown by connected triangles up, and using its 2000 updated version, YIELDX2k \[35\], by connected triangles down.
will not discuss such them here; instead, we will apply the merged LAQGSM+GEM2 code to analyze reactions on the same $^{208}\text{Pb}$-target (projectile, in the case of the inverse kinematics of the GSI measurements [10]), but induced by deuterons.

A- and Z-distributions of the nuclides produced in the d(1 GeV/nucleon) + Pb reaction calculated with the LAQGSM+GEM2 code are compared in Fig. 10 with the GSI data [10]. As in case of proton-induced reactions, we get a correct fission cross section only by adjusting the ratio of level density parameters in the fission and evaporation channels $a_f/a_n$ in Eq. (5), or, equivalently, by adjusting $a_f^{\text{CEM}}/a_f^{\text{RAL}}$, if we use $a_f^{\text{RAL}}$ provided by Eq. (5). We get a correct fission cross section for $a_f^{\text{CEM}}/a_f^{\text{RAL}} = 1.15$ in the “with Prec” case (short-dashed lines in Fig. 10) and for $a_f^{\text{CEM}}/a_f^{\text{RAL}} = 0.97$ in the case of “no Prec” (long-dashed lines in Fig. 10) when calculating with LAQGSM+GEM2 both p- and d-induced reactions on Pb at 1 GeV/nucleon. Note that these values differ slightly from the ones obtained above for the CEM2k+GEM2 code (see Fig. 3). This can be easily understood, as the INC of LAQGSM differs from the INC of CEM2k, therefore the nuclei simulated by LAQGSM+GEM2 and CEM2k+GEM2 to really fission after the cascade and pre-equilibrium stages of reaction and after evaporation of several particles from compound nuclei before fission have slightly different average values of $A$, $Z$, and $E^*$. 

The agreement (or disagreement) of the LAQGSM+GEM2 results with these data is similar to what we get for the p+Pb reaction: the “no Prec” version provides a good description of both mass and charge distributions and agrees better with the data for these characteristics than the “with Prec” version. These results, together with the ones discussed above for p+Pb reactions, as well as results for many other p+A and A+A reactions measured at GSI at about 1 GeV/nucleon and analyzed with our codes suggest us that we need to take into account pre-equilibrium processes, but we need less emission of pre-equilibrium particles than provided by our standard CEM2k and LAQGSM codes. We address this problem following Veselsky [36]. It is assumed that the ratio of the number of quasiparticles (excitons) $n$ at each pre-equilibrium reaction stage to the number of excitons in equilibrium configuration $n_{eq}$ corresponding to the same excitation energy, to be the crucial parameter for determining the probability of pre-equilibrium emission $P_{pre}$. This probability for a given pre-equilibrium reaction stage is evaluated using the formula

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

for $n \leq n_{eq}$ and equal to zero for $n > n_{eq}$. The basic assumption leading to Eq. (9) is that $P_{pre}$ depends exclusively on the ratio $n/n_{eq}$ as can be deduced from the results of Böhnig [37] 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 no dependence on excitation energy is assumed [36]. Our calculations of several reactions using different values of $\sigma_{pre}$ show that an overall reasonable agreement with available data can be obtained using $\sigma_{pre} = 0.4$ or 0.5 (see Fig. 11). We choose the fixed value $\sigma_{pre} = 0.4$ both for CEM2k+GEM2 and LAQGSM+GEM2 for all our further calculations.

Results with reduced pre-equilibrium emission according to Eq. (9) using $\sigma_{pre} = 0.4$ are shown in Fig. 10 with solid lines (and in the lower plot of Fig. 5 for p+Pb reactions); they agree better with the data than either “with Prec” or “no Prec” standard results.
Figure 10. Comparison of the experimental mass and charge distributions of the nuclides produced in the reaction $d(1 \text{ GeV/nucleon}) + ^{208}\text{Pb}$ (circles show data from Tabs. 2 and 3 and squares - from Fig. 13 of Ref. [10]) with different calculations. The short-dashed lines show results found by merging LAQGSM with GEM2 when preequilibrium emission is included and $a_{f}^{\text{CEM}}/a_{f}^{\text{RAL}} = 1.15$, the long-dashed lines show the results without preequilibrium emission for $a_{f}^{\text{CEM}}/a_{f}^{\text{RAL}} = 0.97$, and the solid lines show the results with reduced preequilibrium emission using $\sigma_{\text{pre}} = 0.4$ and $a_{f}^{\text{CEM}}/a_{f}^{\text{RAL}} = 0.975$; see text for details.

Fig. 11 shows a comparison of the experimental data on production yields of ten separate isotopes with $Z$ lying from 35 to 82 from the same reaction measured at GSI [10] with our LAQGSM+GEM2 calculations using both the “with Prec” and “no Prec” (upper plot) versions, and when calculated with the version of reduced preequilibrium emission according to Eq. (9) (lower plot). One can see that as in the case of the p+Pb
reaction (see lower plot in Fig. 5), calculations with reduced preequilibrium emission agree much better with experimental data than either standard “with Prec” or “no Prec” versions. Similar results were obtained for all other p+A and A+A reactions measured at GSI and calculated by our codes. Therefore we choose the version with reduced preequilibrium emission with a fixed value of $\sigma_{\text{pre}}$ of 0.4 as our “standard” version both for CEM2k+GEM2 and LAQGSM+GEM2, and all our further calculations will be done in this approach.

Fig. 12 shows a comparison of the experimental [10] A-distribution of the mean kinetic energies of the spallation-residue products from the same reaction with different calculations by LAQGSM+GEM2. One can see that for this particular reaction all calculations agree well with the data, with a slightly better agreement for the version with reduced preequilibrium emission. Similar results were obtained for the $Z$-distribution of products from this reaction.

Finally, for completeness sake, the last four figures (Figs. 13–16) show a comparison of all cross sections measured at GSI for the production of nuclides both from spallation and fission reactions from interaction of $^{208}$Pb beams with p and d targets compared with our “standard” LAQGSM+GEM2 results. One can see a very good overall agreement, taking into account that we use here our “standard” version of the code and no further fitting of any parameters is done. Similar results were obtained with standard versions of CEM2k+GEM2 and LAQGSM+GEM2 for many other p+A and A+A reactions measured recently at GSI. Such results will be presented in a separate publication.

**Further Work**

Merging the Generalized Evaporation Model code GEM2 by Furihata [7, 8] with our CEM2k and LAQGSM codes allows us to describe reasonably well many fission and fragmentation reactions in addition to the spallation reactions already described well by CEM2k and LAQGSM. But to do so, one needs to provide first a correct description of the fission cross sections by fitting in GEM2 the ration $a_f/a_n$ for pre-actinides and/or the parameter $C(Z)$ in Eq. (7) for actinides. This is not a serious problem and we have derived already new approximations for $a_f/a_n$ and for parameter $C(Z)$ in Eq. (7) that provide for CEM2k+GEM2 and LAQGSM+GEM2 correct fission cross section calculation both for pre-actinides and actinides for a large range of projectile energies. Such new approximations will be presented together with examples of our results in a separate publication.

Some reactions, like production of fission fragments at the borders between fission and fragmentation or between fission and emission of heavy fragments like Na and Mg are poorly described by CEM2k+GEM2 and LAQGSM+GEM2 in their current versions. This disagreement does not discourage us; the results of the present work suggest that some of the fission and evaporation parameters of GEM2 can be adjusted to get a much better description of all reactions. This lends credibility to such an approach.
Figure 11. Experimental [10] mass distributions of the cross sections of ten isotopes with the charge $Z$ from 35 to 82 compared with our LAQGSM+GEM2 calculations. “With Prec” and “no Prec” results are shown on the upper plot, while results with reduced preequilibrium emission according to Eq. (9) using $\sigma_{\text{prec}} = 0.4$ and 0.5 are shown on the lower one.
Figure 12. Comparison of the experimental [10] mass distribution of the spallation-residue kinetic energies of the nuclides produced in the reaction d(1 GeV/nucleon) + Pb (circles) with the same LAQGSM+GEM2 calculations as shown in Fig. 10.

There is one more drawback of this approach to be mentioned: considering evaporation of up to 66 particles in GEM becomes extremely time consuming when calculating reactions with heavy targets at high incident energies. But even this disadvantage may be mitigated by the performance of modern computers. We have nevertheless some more serious doubts about the current version of GEM2 related to its lack of self-consistency, e.g.:

1) using different, not physically related parameterizations for inverse cross sections and Coulomb barriers for different particles and fragments;

2) using different level density parameters for the same compound nuclei when calculating evaporation and estimating fission probability from the widths of neutron evaporation and fission;

3) different, and purely phenomenological treatments of fission for pre-actinide and actinide nuclei;

4) not taking into account at all the angular momentum of compound and fissioning nuclei;

5) rough estimations for the fission barriers and level density parameters, etc.

This means that an approach like GEM2 can in principle be used to describe fission and evaporation of particles and fragments heavier that $^4$He after the INC and preequilibrium parts of CEM2k, LAQGSM, and other models, but it should be considerably improved striving first to progressively incorporate better physics, and only after that adjusting to selected data.
Figure 13. Comparison of all measured cross sections of spallation products from the reaction 1 GeV/nucleon $^{208}$Pb on p (black circles) with our LAQGSM+GEM2 results (open circles).
Figure 14. Comparison of all measured [9] cross sections of fission products from the reaction 1 GeV/nucleon $^{208}$Pb on p (black circles) with our LAQGSM+GEM2 results (open circles).
Figure 15. Comparison of all measured cross sections of spallation products from the reaction 1 GeV/nucleon $^{208}$Pb on d (black circles) with our LAQGSM+GEM2 results (open circles).
Figure 16. Comparison of all measured cross sections of fission products from the reaction 1 GeV/nucleon $^{208}$Pb on d (black circles) with our LAQGSM+GEM2 results (open circles).
The results of the present work and from [11] show that on the whole, the merged CEM2k+GEM2 and LAQGSM+GEM2 codes agree better with most of tested experimental data when we take into account the preequilibrium emission of particles, than when we neglect completely preequilibrium processes. But there is still a not so clear question here: we have had some indications for many years that CEM accounts for too many preequilibrium particles, at least at energies above the pion-production threshold. To solve this problem, as a “zero-step” approximation, in our original CEM2k version [1] we neglected in the exciton model the transitions that decrease or do not change the number of excitons $\Delta n = -2$ and $\Delta n = 0$, shortening in this way the preequilibrium stage of reactions. We do not like this approach as it is somehow arbitrary, “ad hoc”, even though this “never come back” approximation is used in some popular codes like LAHET [23] and FLUKA [38]. In the present work we removed this arbitrary condition in CEM2k and the “with Prec” version takes into account all the preequilibrium transitions $\Delta n = +2, 0,$ and -2, making the preequilibrium stage of a reaction longer and increasing the number of emitted preequilibrium particles. The results of the present work indicate to us once again that we need to take into account the preequilibrium stage in reactions, but we need less particle emission than we calculate at this stage with the standard version of CEM. In the present paper we address this problem reducing the number of emitted preequilibrium particles following Veselsky [36], as described above.

Besides GEM2, we have investigated the well known code GEMINI by Charity [39] as an alternative way to describe production of various fragments by merging GEMINI with both our CEM2k and LAQGSM, and we tested also the thermodynamical fission model by Stepanov [40] with its own parameterizations for mass and charge widths, level-density parameters, fission barriers, etc., merging it with both CEM2k and LAQGSM to describe fission. In addition, we have started to extend CEM2k and LAQGSM and to develop our own fission model, as briefly noted in [11]. The preliminary results we found for spallation, fission, and fragmentation products from several reactions we tested so far using these approaches are very promising and we will present our results from these studies in several separate papers.

Acknowledgment

We thank Dr. Shiori Furihata for several useful discussions, for sending us her Generalized Evaporation Model code GEM, and providing us further with its updated version, GEM2. We are grateful to Dr. William B. Wilson for providing us with results of his calculation the reaction $p(100 \text{ MeV}) + ^{238}\text{U}$ with the codes CYF and YIELDX2k. We thank Prof. Takashi Nakamura and Drs. Yoshiyuki Iwata and Hiroshi Iwase for sending us numerical values of their measured neutron spectra from heavy-ion reactions and results of their calculations with QMD and HIC.

This study was supported by the U. S. Department of Energy and by the Moldovan-U. S. Bilateral Grants Program, CRDF Project MP2-3025.
References

[1] S. G. Mashnik and A. J. Sierk, “CEM2k—Recent Developments in CEM,” Proc. AccApp’00 (Washington DC, USA), pp. 328–341, La Grange Park, IL, USA, 2001; Eprint: nucl-th/0011064; see also S. G. Mashnik and A. J. Sierk, “Recent Developments of the Cascade-Exciton Model of Nuclear Reactions,” Proc. ND2001 (Tsukuba, Japan), J. Nucl. Sci. Techn., Supplement 2, 720–725 (2002); Eprint: nucl-th/0208074.

[2] K. K. Gudima, S. G. Mashnik, and A. J. Sierk, “User Manual for the Code LAQGSM,” Los Alamos National Report LA-UR-01-6804, Los Alamos (2001).

[3] MCNPX™ User’s Manual, Version 2.3.0, edited by Laurie S. Waters, Los Alamos National Laboratory Report LA-UR-02-2607, Los Alamos (2002).

[4] S. G. Mashnik and A. J. Sierk, “Improved Cascade-Exciton Model of Nuclear Reactions”, Proc. Fourth Int. Workshop on Simulating Accelerator Radiation Environments (SARE-4), Knoxville, TN, USA, September 13–16, 1998, edited by T. A. Gabriel, ORNL (1999), pp. 29–51; Eprint: nucl-th/9812069.

[5] 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).

[6] 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).

[7] S. Furihata, “Statistical Analysis of Light Fragment Production from Medium Energy Proton-Induced Reactions,” Nucl. Instr. Meth. B171, 252–258 (2000); Eprint: nucl-th/0003036; S. Furihata, “The GEM Code — The Generalized Evaporation Model and the Fission Model,” Proc. of the Monte Carlo 2000 Conference, Lisbon, Portugal, 23-26 October 2000, Springer Verlag, p. 1045 (2001); S. Furihata, “The Gem Code Version 2 Users Manual,” Mitsubishi Research Institute, Inc., Tokyo, Japan (2001).

[8] Shiori Furihata et al., “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).

[9] T. Enqvist, W. Wlazlo, P. Armbruster, J. Benlliure, M. Bernas, A. Boudard, S. Czajkowski, R. Legrain, S. Leray, B. Mustapha, M. Pravikoff, F. Rejmund, K.-H. Schmidt, C. Stéphan, J. Taieb, L. Tassan-Got, and C. Volant, “Isotopic Yields and Kinematic Energies of Primary Residues in 1A GeV 208Pb + p Reactions,” Nucl. Phys. A686, 481–524 (2001).
[10] T. Enqvist, W. Wlazlo, P. Armbruster, J. Benlliure, M. Bernas, A. Boudard, S. Czaikowski, R. Legrain, S. LeRay, B. Mustapha, M. Pravikoff, F. Rejmund, K.-H. Schmidt, C. Stéphan, J. Taieb, L. Tassan-Got, and C. Volant, “Primary-residue Production Cross Sections and Kinetic Energy in 1A GeV $^{208}$Pb + on Deuteron Reactions,” *Nucl. Phys.* A703, 435–465 (2002).

[11] S. G. Mashnik, A. J. Sierk, and K. K. Gudima, “Complex-Particle and Light-Fragment Emission in the Cascade-Exciton Model of Nuclear Reactions,” *Proc. RPSD 2002 (Santa Fe, NM)*; LANL Report LA-UR-02-5185, Los Alamos (2002); Eprint: [nucl-th/0208048](http://www.arXiv.org/abs/nucl-th/0208048).

[12] 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,” Proc. Second World Space Congress, COSPAR 2002, Houston, TX, USA, October 10–19, 2002; LA-UR-02-6558, Los Alamos (2002); Eprint: [nucl-th/0210065](http://www.arXiv.org/abs/nucl-th/0210065) to be published in the journal *Advances in Space Research*.

[13] K. K. Gudima, S. G. Mashnik, and V. D. Toneev, “Cascade-Exciton Model of Nuclear Reactions,” *Nucl. Phys.* A401, 329–361 (1983).

[14] S. G. Mashnik, “User Manual for the Code CEM95,” JINR, Dubna (1995); OECD NEA Data Bank, Paris, France (1995); [http://www.nea.fr/abs/html/iaea1247.html](http://www.nea.fr/abs/html/iaea1247.html); RSIC-PSR-357, Oak Ridge (1995).

[15] Yu. E. Titarenko et al., “Cross Sections for Nuclide Production in 1 GeV Proton-Irradiated Pb”, *Phys. Rev.* C65, 064610 (2002); E-print: [nucl-th/0011083](http://www.arXiv.org/abs/nucl-th/0011083).

[16] N. S. Amelin, K. K. Gudima, and V. D. Toneev, “Ultrarelativistic Nucleus-Nucleus Collisions in a Dynamical Model of Independent Quark-Gluon Strings,” *Sov. J. Nucl. Phys.* 51, 1093–1101 (1990) [Yad. Fiz. 51, 1730–1743 (1990)]; 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,” *Sov. J. Nucl. Phys.* 52, 172–178 (1990) [Yad. Fiz. 52, 272–282 (1990)]; N. S. Amelin, “Simulation of Nuclear Collisions at High Energy in the Framework of the Quark-Gluon String Model,” Joint Institute for Nuclear Research Report JINR-86-802, Dubna (1986).

[17] V. D. Toneev and K. K. Gudima, “Particle Emission in Light and Heavy-Ion Reactions,” *Nucl. Phys.* A400, 173c–190c (1983).

[18] K. Ishibashi, H. Takada, T. Nakomoto, N. Shigyo, K. Maehata, N. Matsufuji, S. Meigo, S. Chiba, M. Numajiri, Y. Watanabe, T. Nakamura, “Measurement of Neutron-Production Double-Differential Cross Sections for Nuclear Spallation Reaction Induced by 0.8, 1.5 and 3.0 GeV Protons”, *J. Nucl. Sci. Techn.*, 34, 529–537 (1997).
[19] Y. Iwata, T. Murakami, H. Sato, H. Iwase, T. Nakamura, T. Kurowsawa, L. Heibronn, R. M. Ronningen, K. Ieki, Y. Tozawa and K. Niita, “Double-differential Cross Sections for the Neutron Production from Heavy-ion Reactions at Energies $E/A = 290 - 600$ MeV”, Phys. Rev. C64, 054609 (2001).

[20] J. Aichelin, “Quantum Molecular Dynamics – a Dynamical Microscopic $n$-body Approach to Investigate Fragment Formation and Nuclear Equation of State in Heavy Ion Collisions”, Phys. Rep. 202, 233–360 (1991).

[21] H. W. Bertini, T. A. Gabriel, R. T. Santoro, O. W. Hermann, N. M. Larson and J. M. Hunt, “HIC-1: A First Approach to the Calculation of Heavy-ion Reactions at Energies $\geq 50$ MeV/Nucleon”, Oak Ridge National Laboratory Report ORNL-TM-4134, Oak Ridge (1974).

[22] I. Dostrovsky, Z. Frankel, and G. Friedlander, “Monte Carlo Calculations of Nuclear Evaporation Processes. III. Application to Low-Energy Reactions,” Phys. Rev. 116, 683–702 (1959).

[23] R. E. Prael and H. Lichtenstein, “User Guide to LCS: The LAHET Code System,” LANL Report No. LA-UR-89-3014, Los Alamos (1989); http://www-xdiv.lanl.gov/XTM/lcs/laht-doc.html

[24] Shiori Furihata and Takashi Nakamura, “Calculation of Nuclide Production from Proton Induced Reactions on Heavy Targets with INC/GEM,” Proc. ND2001 (Tsukuba, Japan), J. Nucl. Sci. Techn., Supplement 2, 758–761 (2002).

[25] V. F. Weisskopf and D. H. Ewing, “On the Yield of Nuclear Reactions with Heavy Elements,” Phys. Rev. 57, 472–485 (1940).

[26] Robert Vandenbosch and John R. Huizenga, Nuclear Fission, Academic Press, New York (1973).

[27] F. Atchison, “A Revised Calculational Model for Fission,” Paul Scherrer Insstitut Report No. 98-12, Villigen PSI (1998).

[28] H. W. Bertini, “Low-Energy Intranuclear Cascade Calculation,” Phys. Rev. 131, 1801–1871 (1963); “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, 1711–1730 (1969).

[29] Y. Yariv and Z. Frankel, “Intranuclear Cascade Calculation of High-Energy Heavy-Ion Interactions,” Phys. Rev. C20, 2227–2243 (1979); “Inclusive Cascade Calculation of High Energy Heavy Ion Collisions: Effect of Interactions between Cascade Particles,” Phys. Rev. C24, 488–494 (1981).

[30] S. G. Mashnik, A. J. Sierk, K. A. Van Riper, and W. B. Wilson, “Production and Validation of Isotope Production Cross Section Libraries for Neutrons and Protons to 1.7 GeV,” Proc. Fourth Workshop on Simulating Accelerator Radiation Environments (SARE4), Knoxville, TN, USA, September 14–16, 1998, edited by T. A. Gabriel,
ORNL (1999), pp. 151–162; Eprint: nucl-th/9812071; our compilation (T-16 Lib) is permanently updated as new data become available to us.

[31] R. E. Segel, T. Chen, L. L. Rutledge, Jr., J. V. Maher, John Wiggins, P. P. Singh, and P. T. Debevec, “Inclusive Proton Reactions at 164 MeV,” Phys. Rev. C26, 2424–2432 (1982).

[32] Yury E. Titarenko et al., “Experimental and Theoretical Study of the Yields of Radionuclides Produced in natU Thin Targets Irradiated by 100 and 800 MeV Protons,” Proc. 3rd Int. Conf. on Accelerator Driven Transmutation Technologies and Applications (ADTTA'99), Praha (Pruhonice), 7–11 June 1999, Czech Republic, Paper # P-C25 on the ADTTA’99 Web page http://www.fiji.cvut.cz/con_adtt99/s_confer/a_info/list_pap.htm and on the conference CD; numerical values of measured cross sections are tabulated in Yu. E. Titarenko, “Experimental and Theoretical Study of the Yields of Residual Product Nuclei Produced in Thin Targets Irradiated by 100–2600 MeV Protons,” Final Project Technical Report of ISTC 839B-99, ITEP, Moscow (2001); INDC(CCP)-434, http://www-nds.iaea.org/reports/indc-ccp-434.pdf.

[33] Arthur C. Wahl, “Systematics of Fission-Product Yields,” Los Alamos National Laboratory Report LA-UR-01-5944, Los Alamos (2001).

[34] R. Silberberg, C. H. Tsao, and A. F. Barghouty, “Updated Partial Cross Sections of Proton-Nucleus Reactions,” Astrophys. J. 501, 911–919 (1998).

[35] R. Silberberg, C. H. Tsao, and A. F. Barghouty, The 2000 Version of the code YIELDX; C. H. Tsao, private communication to Dr. W. Wilson, T-16, LANL (2002).

[36] M. Veselsky, “Production Mechanism of Hot Nuclei in Violent Collisions in the Fermi Energy Domain,” Nucl. Phys. A705, 193–222 (2002); Eprint: nucl-th/0107062_v3; M. Veselský, Š. Šáro, F. P. Heßberger, V. Ninov, S. Hofmann, and D. Ackermann, “Production of Fast Evaporation Residues by the Reaction 20Ne + 208Pb at Projectile Energies of 8.6, 11.4 and 14.9 A MeV,” Z. Phys. A356, 403–410 (1997).

[37] M. Böhning, “Density of Particle-hole States in the Equidistant-spacing Model,” Nucl. Phys. A152, 529–546 (1970).

[38] A. Ferrari and P. R. Sala, “The Physics of High Energy Reactions”, Proc. Workshop on Nuclear Reaction Data and Nuclear Reactors Physics, Design and Safety, ICTP, Miramare-Trieste, Italy, 15 April–17 May 1996, World Scientific, A. Gandini, G. Reffo, Eds, Vol. 2, p. 424-532 (1998) and references therein.

[39] R. J. Charity et al., “Systematics of Complex Fragment Emission in Niobium-induced Reactions”, Nucl. Phys. A483, 371–405 (1988); “Emission of Unstable Clusters from Yb Compound Nuclei,” Phys. Rev. C63, 024611 (2001); http://wunmr.wustl.edu/~rc/
[40] N. V. Stepanov, “Statistical Simulation of Excited Nuclei Fission. 1. Formulation of the Model”, ITEP Preprint 81 (1987), Institute for Theoretical and Experimental Physics, Moscow, USSR (1987).