Title: Overview and Validation of the CEM03.03 and LAQGSM03.03 Event Generators for the MCNP6, MCNPX, and MARS15 Transport Codes

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Overview and Validation of the CEM03.03 and LAQGSM03.03 Event Generators for the MCNP6, MCNPX, and MARS15 Transport Codes

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Reliable models of intermediate and high energy nuclear reactions are important to a number of applications at Los Alamos National Laboratory, including such projects as the Accelerator Transmutation of nuclear Wastes (ATW), Accelerator Production of Tritium (APT), Spallation Neutron Source (SNS), Rare Isotope Accelerator (RIA), Proton Radiography (PRAD) as a radiographic probe for the Advanced Hydro-test Facility, NASA needs, and others. The US Department of Energy had supported during the last decade our work on the development of improved versions of the Cascade-Exciton Model (CEM) and of the Los Alamos version of the Quark Gluon String Model (LAQGSM) which has led to our intermediate- and high-energy event generators CEM03.03 and LAQGSM03.03 for the transport codes MCNP6, MCNPX, and MARS15.

I shall discuss some recent research at Los Alamos to improve our nuclear reaction models. Namely, I will present a description of the IntraNuclear Cascade (INC), preequilibrium, evaporation, fission, coalescence, and Fermi breakup models used by the latest versions of our CEM03.03 and LAQGSM03.03 event generators, with a focus on our most recent developments of these models. The recently developed “S” and “G” versions of our codes, that consider multifragmentation of nuclei formed after the preequilibrium stage of reactions when their excitation energy is above 2A MeV using the Statistical Multifragmentation Model (SMM) code by Botvina et al. (“S” stands for SMM) and the fission-like binary-decay model GEMINI by Charity (“G” stands for GEMINI), respectively, will be briefly described as well. Examples of benchmarking our models against a large variety of experimental data on particle-particle, particle-nucleus, and nucleus-nucleus reactions will be presented. Open questions on reaction mechanisms and future necessary work will be outlined.

The presented work was carried out under the auspices of the National Nuclear Security Administration of the U.S. Department of Energy at Los Alamos National Laboratory under Contract No. DE-AC52-06NA25396.
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Many people participated in development of the Cascade-Exciton Model (CEM) and Los Alamos version of the Quark-Gluon String Model (LAQGSM) over their almost 40-year history.

The current contributors are:

A recent lecture with many references on our work may be found in:
• Introduction

• INC of CEM03.03 and LAQGSM03.03

• The coalescence model

• Preequilibrium [the Modified Exciton Model (MEM)]

• Evaporation

• Fission

• Fermi break-up of light nuclei (A<13)

• Fission-like binary-decay by GEMINI and multifragmentation by the Statistical Multifragmentation Model (SMM) in the "G" and "S" versions of CEM03.01 and LAQGSM03.01

• Summary
A general scheme of CEM/LAQGSM calculation

Input

IntraNuclear Cascade (INC)
A > 13?

no

Preequilibrium
A > 13?

no

Evaporation
A > 13?

Fission, if Z>64
A_{f1}, A_{f2}, > 13?

no

yes

Coalescence

n and p

d, t, ³He, ⁴He

Fermi breakup

Evaporation from fission fragments
A > 13?

Output

Computational Analysis and Simulation (X-3)
The INC of CEM03.03 is based on the "standard" (non-time-dependent) version of the Dubna cascade model [1,2], improved and developed further at LANL during recent years [3-6]:


The nuclear matter density $\rho(r)$ is described by a Fermi distribution

$$\rho(r) = \rho_p(r) + \rho_n(r) = \rho_0 \left\{ 1 + \exp\left[\frac{(r - c)}{a}\right] \right\}$$

where $c = 1.07A^{1/3}$ fm and $a = 0.545$ fm

the target nucleus is divided by concentric spheres into seven zones

The energy spectrum of the target nucleons is estimated with the local Fermi energy $T_F(r) = \hbar^2 [3\pi^2 \rho(r)]^{2/3} / (2m_N)$
\[ NN \rightarrow NN, \quad NN \rightarrow \pi NN, \quad NN \rightarrow \pi_1, \cdots, \pi_i NN \]
\[ \pi N \rightarrow \pi N, \quad \pi N \rightarrow \pi_1, \cdots, \pi_i N \quad (i \geq 2) \]
\[ \pi NN \rightarrow NN \]

\[ \sigma_{\gamma A} = L \frac{Z(A - Z)}{A} \sigma_{\gamma d} \]

\[ \gamma + p \rightarrow p + \pi^0, \]
\[ \rightarrow n + \pi^+, \]
\[ \rightarrow p + \pi^+ + \pi^-, \]
\[ \rightarrow p + \pi^0 + \pi^0, \]
\[ \rightarrow n + \pi^+ + \pi^0. \]

\[ V \equiv V_N(r) = T_F(r) + \epsilon, \quad V_\pi \approx 25 \text{ MeV}, \]

Pauli principle forbids a number of intranuclear collisions
Graphs showing cross-section data for various reactions:

- \( n + p \) total cross section
- \( n + p \rightarrow p + p + \pi^- (\times 1000) \)
- \( \pi^+ + p \) total nuclear cross section
- \( \pi^+ + p \rightarrow \pi^+ + p + \pi^0 (\times 10) \)
- \( \gamma + p \) total cross section
- \( \gamma + p \rightarrow n + \pi^+ + \pi^0 (\times 10) \)

The graphs include experimental data and approximations by CEM95 and CEM97.
The cosine of the angle of emission of secondary particles in the c.m. system is calculated by the Dubna INC as a function of a random number $\xi$, distributed uniformly in the interval [0,1] as

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

where $N= M= 3$, 

$$a_n = \sum_{k=0}^{M} a_{nk} T^k \gamma ,$$

where 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.

The distribution of secondary particles over the azimuthal angle $\phi$ 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.
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 new approximations analogous to the ones described above, since reliable systematics have been developed recently by Joseph Cugnon et al. for the Liege INC, then improved still further by Helder Duarte for the BRIC code; we simply incorporate into CEM03.01 the systematics by Duarte.


Proc. 10th Int. Conf. on Nuclear Reaction Mechanisms, Varenna, Italy, June 9-13, 2003; http://lxmi.mi.infn.it/~gadioli/registered.htm;
Similarly, for $\gamma p$ and $\gamma n$ interactions, we take advantage of the event from the Moscow INC kindly sent us by its coauthor, 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 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 $\zeta$ uniformly distributed in the interval $[0,1]$.

$d\sigma_{np}/d\Omega$ (mb/sr)

$T_n=386$ MeV
$T_n=418$ MeV
$T_n=473$ MeV
$T_n=532$ MeV
$T_n=636$ MeV
$T_n=684$ MeV
$T_n=770$ MeV
$T_n=801$ MeV
$T_n=899$ MeV
$T_n=986$ MeV
$T_n=1073$ MeV
$T_n=1243$ MeV

New
Old
The initial versions of CEM, just like LAQGSM and other INC-type models, calculate the total reaction cross section, using the geometrical cross section, and the number of inelastic, and elastic, simulated events, namely:

\[ \sigma_{in} = \sigma_{geom} N_{in}/(N_{in} + N_{el}). \]

This approach provides a reasonable good agreement with available data at incident energies above about 100 MeV, but is not reliable at lower bombarding energies and for some photonuclear reactions. To address this problem, we have incorporated into CEM2k the NASA systematics by Tripathi et al. for all incident protons and neutrons with energies above the maximum in the NASA reaction cross sections, the Kalbach systematics for neutrons of lower energy, and, in CEM03.01, the Kossov systematics for all photonuclear reactions:


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In comparison with the initial version [1,2] of INC, in CEM03.03 we have:

1) Developed better approximations for the total elementary cross sections;
2) Developed new approximations to describe more accurately experimental elementary energy and angular distributions of secondary particles from hadron-hadron and photon-hadron interactions;
3) Normalized photonuclear reactions to detailed systematics developed by M. Kossov and nucleon-induced reactions, to NASA and Kalbach systematics;
4) The condition for transition from the INC stage of a reaction to preequilibrium was changed; on the whole, the INC stage in CEM03.03 is longer while the preequilibrium stage is shorter in comparison with previous versions;
5) Incorporation of real binding energies for nucleons in the cascade instead of the approximation of a constant separation energy of 7 MeV used in the initial versions of the CEM; imposing momentum-energy conservation for each simulated even (provided only “on the average” by the initial versions);
6) The algorithms of many INC routines were changed and almost all INC routines were rewritten, which speeded up the code significantly;
7) Some preexisting bugs in the INC were fixed.
The INC stage of reactions is described by LAQGSM03.03 with a recently improved version [1] of the time-depending intranuclear cascade model developed initially in Dubna, often referred in the literature simply as the Dubna intranuclear Cascade Model, DCM [2], using the Quark-Gluon String Model (QGSM) [3] to describe elementary interactions at energies above 4.5 GeV.

LAQGSM uses a continuous nuclear distribution (no "zones")

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

where \( c = 1.07A^{1/3} \text{ fm} \), and \( a = 0.545 \text{ fm} \)

Before starting to simulate an INC event, position of all IntraNuclear nucleons are simulated and "frozen"
The projectile interacts (in point A) with the nearest target nucleon met inside the cylinder with the radius $r$

$$r = r_{\text{int}} + \lambda/2\pi,$$

where $r_{\text{int}} = 1.3$ fm; $\lambda/2\pi$ is the de Broglie wavelength
$t_{f}^{(2,3,...)}$ is the formation time of the cascade particle #1(2,3,...)

If $t_2 < t_1$, $t_2 < t_3$, ..., and $t_2 > t_{f2}$, particle #2 interacts first in point C

IntraNuclear nucleons involved in interactions become "cascade" particles and are removed from the status of "frozen" target nucleons (trailing effect)

The formation time: $t_{f} = (E/m)t_{f}^{0}$; $t_{f}^{0} = C_{t} \hbar/m_{\pi}$;

$C_{t} = 1.0$ for mesons and $\sim 0.0$ for baryons
New approximations for $\gamma p$ and $\gamma n$ cross sections from A. S. Iljinov et al., Nucl. Phys. A616 (1997) 575, kindly provided us by Dr. Igor Pshenichnov, have been incorporated into LAQGSM03.01.
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Experimental data:

LAQGSM03.03 results: histograms
The coalescence model implemented in LAQGSM/CEM is described in [1]; we have changed the coalescence momentum radii $p_0$ for the various light composite particles up to $^4$He by fitting them to measured data on various reactions and have fixed several bugs observed in the original version [1].


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

**LAQGSM:**

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

**CEM:**

- $p_c(d) = 150$ MeV/c;
- $p_c(t) = P_c(^3\text{He}) = 175$ MeV/c;
- $p_c(^4\text{He}) = 175$ MeV/c
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Data: V. Blideanu et al.,
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\[ p(70\text{GeV}) + \text{Pb} \rightarrow p + X \]
\[ \theta_{\text{lab}} = 160 \text{ mrad} \]

\[ p(70\text{GeV}) + \text{Pb} \rightarrow d + X \]
\[ \theta_{\text{lab}} = 160 \text{ mrad} \]

\[ p(70\text{GeV}) + \text{Pb} \rightarrow t + X \]
\[ \theta_{\text{lab}} = 160 \text{ mrad} \]

35 (1982) 694;
37 (1983) 732;
41 (1985) 227
The preequilibrium part of reactions is described with the latest version [1] of the Modified Exciton Model (MEM) [2,3] from the improved Cascade-Exciton Model (CEM) [4] released in the Code CEM03.01 [1]:


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, $^3$He, and $^4$He.

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

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

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

$$\Gamma_j(p, h, E) = \int_{V^c_j}^{E-B_j} \lambda_c^j(p, h, E, T) dT,$$

$$\lambda^j_c(p, h, E, T) = \frac{2s_j + 1}{\pi^2 \hbar^3} \mu_j R_j(p, h) \frac{\omega(p - 1, h, E - B_j - T)}{\omega(p, h, E)} T \sigma_{inv}(T).$$
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 plan to include preequilibrium emission of clusters heavier than \(^4\text{He}\) in the following versions of our codes.)

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. 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)

\[
\gamma_j \approx p_j^3 \left( \frac{V_j}{V} \right)^{p_j - 1} = p_j^3 \left( \frac{p_j}{A} \right)^{p_j - 1} .
\]

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. In CEM03.01, we fitted \(\gamma_j\) to nucleon-induced reactions experimental spectra.
In comparison with the initial version [2] of CEM, the preequilibrium (PREC) part of CEM03.01 have been changed:

1) the condition for transition from the preequilibrium stage of a reaction to evaporation/fission was changed; on the whole, the preequilibrium stage in CEM03.01 is shorter while the evaporation stage is longer in comparison with previous versions;

2) the widths for complex-particle emission were changed by fitting the probability of several excitons to "coalesce" into a complex particle that may be emitted during the preequilibrium stage to available experimental data on reactions induced by protons and neutrons;

3) Kalbach systematics for angular distribution of complex particles and nucleons with $T < 210$ MeV was incorporated into CEM/LAQGSM;

4) algorithms of many PREC routines were changed and almost all PREC routines were rewritten, which speeded up the code significantly;

5) some old bugs were discovered and fixed.
The evaporation stages of reactions is calculated with an improved version of the Generalized Evaporation Model (GEM2) by Furihata (several routines by Furihata from GEM2 were slightly modified in CEM03.01/LAQGSM03.01; some bugs found in GEM2 were fixed).

\[ P_j(\epsilon)d\epsilon = g_j \sigma_{inv}(\epsilon) \frac{\rho_d(E - Q - \epsilon)}{\rho_i(E)} \epsilon d\epsilon \]

<table>
<thead>
<tr>
<th>( Z_j )</th>
<th>Ejectiles</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>n</td>
</tr>
<tr>
<td>1</td>
<td>p d t</td>
</tr>
<tr>
<td>2</td>
<td>(^3)He (^4)He (^6)He (^8)He</td>
</tr>
<tr>
<td>3</td>
<td>(^6)Li (^7)Li (^8)Li (^9)Li</td>
</tr>
<tr>
<td>4</td>
<td>(^7)Be (^9)Be (^{10})Be (^{11})Be (^{12})Be</td>
</tr>
<tr>
<td>5</td>
<td>(^8)B (^{10})B (^{11})B (^{12})B (^{13})B</td>
</tr>
<tr>
<td>6</td>
<td>(^{10})C (^{11})C (^{12})C (^{13})C (^{14})C (^{15})C (^{16})C</td>
</tr>
<tr>
<td>7</td>
<td>(^{12})N (^{13})N (^{14})N (^{15})N (^{16})N (^{17})N</td>
</tr>
<tr>
<td>8</td>
<td>(^{14})O (^{15})O (^{16})O (^{17})O (^{18})O (^{19})O (^{20})O</td>
</tr>
<tr>
<td>9</td>
<td>(^{17})F (^{18})F (^{19})F (^{20})F (^{21})F</td>
</tr>
<tr>
<td>10</td>
<td>(^{18})Ne (^{19})Ne (^{20})Ne (^{21})Ne (^{22})Ne (^{23})Ne (^{24})Ne</td>
</tr>
<tr>
<td>11</td>
<td>(^{21})Na (^{22})Na (^{23})Na (^{24})Na (^{25})Na</td>
</tr>
<tr>
<td>12</td>
<td>(^{22})Mg (^{23})Mg (^{24})Mg (^{25})Mg (^{26})Mg (^{27})Mg (^{28})Mg</td>
</tr>
</tbody>
</table>
Fission is calculated with an improved version of GEM2 that is an extension by Shiori Furihata of the RAL fission model of Francis Atchison. We have changed the calculation of the fission cross sections; several routines by Furihata from GEM2 were slightly modified in CEM03.03/LAQGSM03.03; some bugs found in GEM2 were fixed.

1) Fission cross section calculation:

1) $70 \leq Z_j \leq 88$ the Weisskopf and Ewing statistical model

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

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

\[
s_n = 2\sqrt{a_n(E - Q_n - \delta)}
\]

\[
a_n = (A_i - 1)/8
\]

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

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

\[
\Gamma_f = \frac{(s_f - 1)e^{s_f} + 1}{a_f}
\]

\[
a_f = a_n \left( 1.08926 + 0.01098(\chi - 31.08551)^2 \right), \text{ and } \chi = Z^2/A.
\]

\[
B_f = Q_n + 321.2 - 16.7\frac{Z_i^2}{A} + 0.218 \left( \frac{Z_i^2}{A_i} \right)^2
\]
2) $Z_j \geq 89$

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

$C(Z)$ and $A_0(Z)$ are constants

In CEM03.03 and LAQGSM03.03, we have adjusted the original values of $a_f/a_n$ and $C(Z)$, namely:

$$a_f \rightarrow C_a \times a_f$$

$$C(Z_i) \rightarrow C_c \times C(Z_i)$$

<table>
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<tr>
<th>$Z$</th>
<th>$C(Z)$</th>
<th>$A_0(Z)$</th>
</tr>
</thead>
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<tr>
<td>89</td>
<td>0.23000</td>
<td>219.40</td>
</tr>
<tr>
<td>90</td>
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<td>91</td>
<td>0.12225</td>
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<td>92</td>
<td>0.14727</td>
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</tr>
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<td>93</td>
<td>0.13559</td>
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</tr>
<tr>
<td>94</td>
<td>0.15735</td>
<td>241.34</td>
</tr>
<tr>
<td>95</td>
<td>0.16597</td>
<td>243.04</td>
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<tr>
<td>96</td>
<td>0.17589</td>
<td>245.52</td>
</tr>
<tr>
<td>97</td>
<td>0.18018</td>
<td>246.84</td>
</tr>
<tr>
<td>98</td>
<td>0.19568</td>
<td>250.18</td>
</tr>
<tr>
<td>99</td>
<td>0.16313</td>
<td>254.00</td>
</tr>
<tr>
<td>100</td>
<td>0.17123</td>
<td>257.80</td>
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<tr>
<td>101</td>
<td>0.17123</td>
<td>261.30</td>
</tr>
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<td>102</td>
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<td>103</td>
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<tr>
<td>104</td>
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<td>105</td>
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<td>275.30</td>
</tr>
<tr>
<td>106</td>
<td>0.17123</td>
<td>278.80</td>
</tr>
</tbody>
</table>
Figure 3. Experimental [31] proton-induced fission cross sections of $^{186}$W, $^{184}$W, $^{183}$W, and $^{182}$W compared with improved (red solid lines) and old (blue dashed lines, from [31]) CEM03.01 calculations.
2) Fission fragments distributions calculation:

**Mass Distribution**

For a pre-fission nucleus with \( Z_i^2/A_i \leq 35 \), only symmetric fission is allowed.

\[
\text{For nuclei with } Z_i^2/A_i > 35, \quad P_{asy} = \frac{4870e^{-0.36E}}{1 + 4870e^{-0.36E}}
\]

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.

\[
\sigma_M = C_3(Z_i^2/A_i)^2 + C_4(Z_i^2/A_i) + C_5(E - B_f) + C_6.
\]

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.
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

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

(62)

where

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

(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 $\sigma_{\epsilon_f}$.

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

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 $\sigma_{\epsilon_f}$

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

(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].
The Fermi breakup model code used in LAQGSM03.03 and in CEM03.03 was developed in the group of Prof. Barashenkov at JINR, Dubna and is described in details in [1].


The total probability per unit time of a nucleus (A,Z) with excitation energy U to breakup into n components is:

\[ W(E, n) = (V/\Omega)^{n-1} \rho_n(E), \quad E = U + M(A, Z), \quad \Omega = (2\pi\hbar)^3 \]

\[ V = 4\pi R^3/3 = 4\pi r_0^3 A/3, \]

where \( r_0 = 1.4 \text{ fm} \), is the only "free" parameter (fixed) of the model.
In comparison with its initial version [1] used in QGSM, we have modified the Fermi breakup model in the "03.02" versions of CEM and LAQGSM:

1) To decay some unstable light fragments like $^5$He, $^5$Li, $^8$Be, $^9$B, etc., that were produced by the original Fermi breakup model;

2) Several bugs/uncertainties observed in the original version [1] were fixed; this solved the problem of the production of "nucleon stars" like "nuclides" $x_n$ and $y_p$ allowed by the original version;

3) We have incorporated the Fermi breakup model at the preequilibrium and evaporation stages of reactions (earlier, it was used only after the INC).
Mass number, $A$ ---

Cross section (mb)

730 MeV $p + A$ I

- CEM03.01, no Fermi break-up in Preco/Evap
- CEM03.02, with Fermi break-up in Preco/Evap
- Data (800 MeV)
The Ammon et al. data and TALYS and INCL+ABLA results are from:
Cross sections for the production of helium, neon and argon isotopes
by proton-induced reactions on iron and nickel

K. Ammon\textsuperscript{a,}\textsuperscript{*}, I. Leya\textsuperscript{a}, B. Lavielle\textsuperscript{b}, E. Gilabert\textsuperscript{b}, J.-C. David\textsuperscript{c}, U. Herpers\textsuperscript{d}, R. Michel\textsuperscript{e}
The Leya et al. data and TALYS and INCL+ABLA results are from:

The Leya et al. data and TALYS and INCL+ABLA results are from:

The Leya et al. data and TALYS and INCL+ABLA results are from:

The FRS GSI data and EPAX and COFRA results are from:

Projectile fragmentation of $^{86}$Kr at 64 MeV/nucleon

M. Mocko,1,2* M. B. Tsang,1,2 Y. Y. Sun,3 N. Aoi,4 J. M. Cook,1,2 F. Delaunay,1 M. A. Famiano,1 H. Hui,1 N. Imai,4 H. Iwasaki,5 W. G. Lynch,1,2 T. Motobayashi,4 M. Niikura,5 T. Onishi,5 A. M. Rogers,1,2 H. Sakurai,5 A. Stolz,1 H. Suzuki,5 E. Takeda,7 S. Takeuchi,4 and M. S. Wallace1,2

Figure 9: Experimental data for $^{86}$Kr+${}^{181}$Ta reactions compared to LAQGSM model.

FIG. 8. Measured cross sections presented as isotope distributions for $25 \leq Z \leq 36$ elements detected in the $^{86}$Kr+${}^{181}$Ta reactions (filled circles) and in the $^{86}$Kr+${}^{9}$Be reactions (open squares) at 64 MeV/nucleon. EPAX calculations are shown as dashed ($^{86}$Kr+${}^{9}$Be) and solid ($^{86}$Kr+${}^{181}$Ta) curves.
Zeitlin et al. data and EPAX2, PHITS, Nilsen et al., and NUCFRG2 results are from:
$E_0 = 1$ GeV bremsstrahlung induced data:
660 MeV p + $^{129}$I

- **data**: $^{129}$I
  - **data**: $^{127}$I + $^{129}$I

- **CEM03.01**
- **CEM03.S1**
- **CEM03.G1**

Experimental and calculated 1.5 GeV p + $^{56}$Fe product yields as functions of A:
Theoretical predictions on $^{56}\text{Fe}(p,x)$ residuals

Comparison with ITEP data
Comparison with GSI data
CEM03.S1 and LAQGSM03.S1 are exactly the same as CEM03.01 and LAQGSM03.01, but consider also multifragmentation of excited nuclei produced after the preequilibrium stage of reactions, when their excitation energy is above 2A MeV, using the Statistical Multifragmentation Model (SMM) by Botvina et al. (the “S” in the extension of CEM03.S1 and LAQGSM03.S1 stands for SMM).

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**Graph 1:**
- **Title:** Cross section (mb)
- **Y-axis:** Logarithmic scale from $10^{-3}$ to $10^4$
- **X-axis:** Mass number $A$
- **Data:**
  - GSI data, 2007
  - CEM03.G1, no t_delay
  - CEM03.G1, t=75, a=50
  - LAOGSM03.G1, no t_delay
  - LAOGSM03.G1, t=75, a=50

**Graph 2:**
- **Title:** Cross section (mb)
- **Y-axis:** Logarithmic scale from $10^{-3}$ to $10^4$
- **X-axis:** Charge number $Z$
- **Data:**
  - GSI data, 2007
  - CEM03.G1, no t_delay
  - CEM03.G1, t=75, a=50
  - LAOGSM03.G1, no t_delay
  - LAOGSM03.G1, t=75, a=50

**Graph 3:**
- **Title:** $\langle T(A) \rangle$ (MeV)
- **Y-axis:** Logarithmic scale from 0 to 70
- **X-axis:** Mass number $A$
- **Data:**
  - GSI data, 2007
  - CEM03.G1, no t_delay
  - CEM03.G1, t=75, a=50
  - LAOGSM03.G1, no t_delay
  - LAOGSM03.G1, t=75, a=50

CEM03.G1 and LAQGSM03.G1 are exactly the same as CEM03.01 and LAQGSM03.01, but uses the fission-like binary-decay model GEMINI of Charity et al., which considers evaporation of all possible fragments, instead of using the GEM2 model (the "G" in the extension of CEM03.G1 and LAQGSM03.G1 stands for GEMINI).

400MeV/u Uranium Beam on 0.2-cm Thick Lithium target

- Pencil beam of U-238 – zero radius
- MCNPX run 1.0e+09 particles in 7:01:50 wall clock hours using 64 processors.
- PHITS run 6.3e+06 particles in 9:18:56 wall clock hours using 64 processors.
- Both runs were in Bassi, last generation IBM parallel machine.
- The ratio is 210.32 times faster for MCNPX.

(Courtesy of Itacil C. Gomes)
Summary

- CEM03.03 and LAQGSM03.03 and their “S” and “G” versions describe nuclear reactions of interest to Spallation Applications better than earlier versions.

- As a rule, CEM03.03 and LAQGSM03.03 describe such reactions not worse than other codes presently available, and are often much faster, which is very important in complex simulations.

- CEM03.01 is available now to users from RSICCC and from NEA/OECD as the Code Package PSR-532.

- The latest versions of our codes, CEM03.03 and LAQGSM03.03, have been or are being incorporated into MCNP6, MCNPX, and MARS15, to be available to users from RSICCC and NEA/OECD.

- There are still some problems important for Spallation Applications to be solved, but we understand the physical basis of these shortcomings and are able to improve predictability as we have done previously.

Thank the Institut Pluridisciplinaire Hubert Curien, and especially, Dr. Johann Bartel, for inviting me to present this seminar and for financial support of my trip!

Merci de votre attention!