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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.

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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:

S. G. Mashnik, K. K. Gudima, A. J. Sierk,
M. I. Baznat, R. E. Prael, N. V. Mokhov.

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

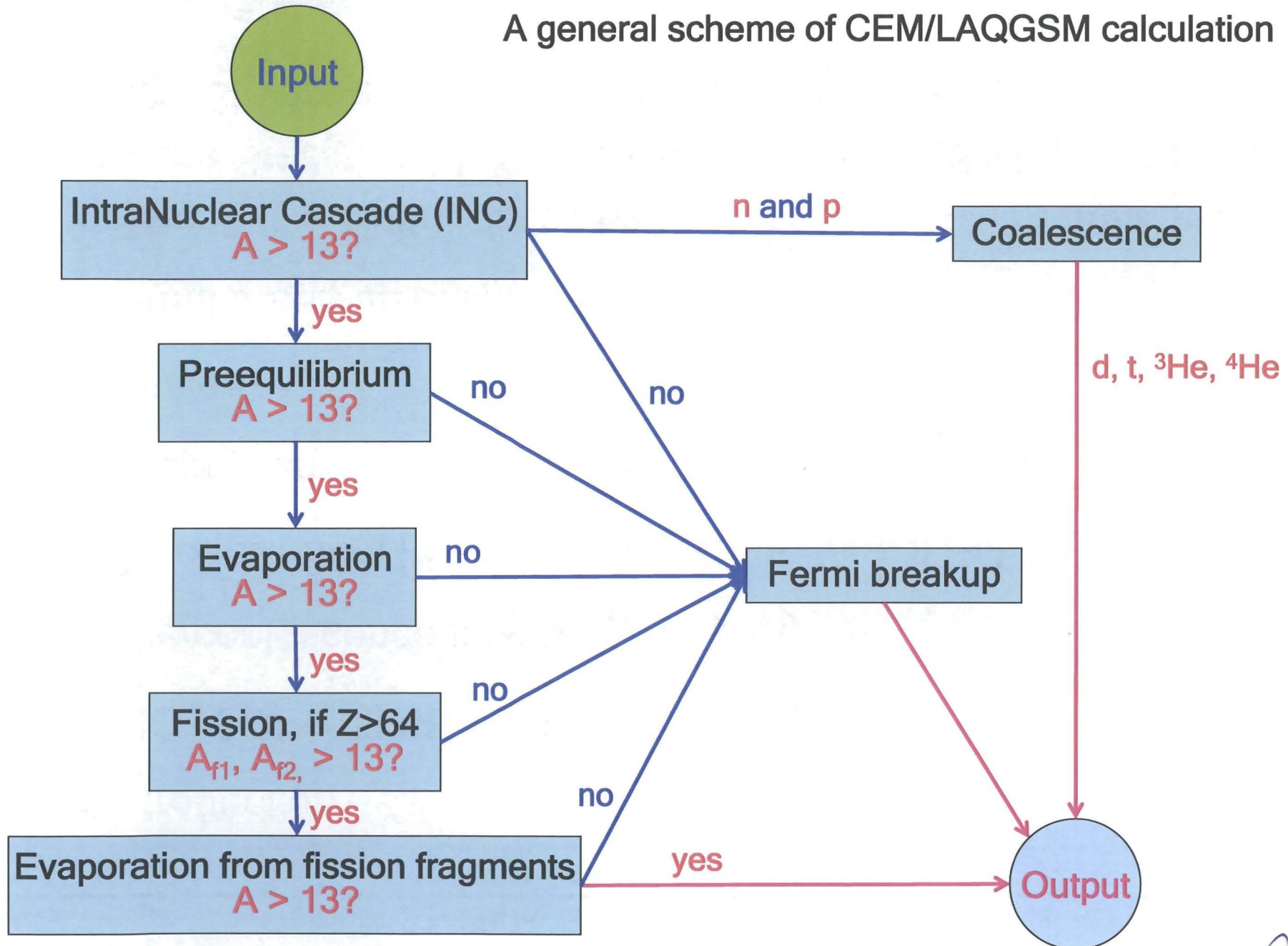
S. G. Mashnik, K. K. Gudima, R. E. Prael, A. J. Sierk, M. I. Baznat, and N. V. Mokhov, *CEM03.03 and LAQGSM03.03 Event Generators for the MCNP6, MCNPX, and MARS15 Transport Codes*, Joint ICTP-IAEA Advanced Workshop on Model Codes for Spallation Reactions, February 4-8, 2008, ICTP, Trieste, Italy, LA-UR-08-2931, Los Alamos (2008), E-print: arXiv:0805.0751.



- 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 **G**EMINI and multifragmentation by the Statistical Multifragmentation Model (**S**MM) in the “**G**” and “**S**” versions of CEM03.01 and LAQGSM03.01
- Summary



A general scheme of CEM/LAQGSM calculation





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]:

- 1) V. S. Barashenkov, K. K. Gudima, and V. D. Toneev, JINR Communications P2-4065 and P2-4066, Dubna (1968); P2-4661, Dubna (1969); Acta Physica Polonica 36 (1969) 415.
- 2) V. S. Barashenkov and V. D. Toneev, *Interaction of High Energy Particle and Nuclei with Atomic Nuclei*, Atomizdat, Moscow (1972); V. S. Barashenkov, *et al.*, Sov. Phys. Usp. 16 (1973) 31.
- 3) S. G. Mashnik and A. J. Sierk, Proc. SARE-4, Knoxville, TN, Sep. 13-16, 1998, pp. 29-51 (nucl-th/9812069).
- 4) S. G. Mashnik and A. J. Sierk, Proc. AccApp00, Washington, DC, USA, Nov. 12-16, 2000, pp. 328-341 (nucl-th/0011064).
- 5) S. G. Mashnik, K. K. Gudima, A. J. Sierk, R. E. Prael, Proc. ND2004, Sep. 26 — Oct. 1, 2004, Santa Fe, NM, AIP Conf. Proc. 769, pp. 1188-1192 (nucl-th/0502019)
- 6) S. G. Mashnik, M. I. Baznat, K. K. Gudima, A. J. Sierk, R. E. Prael, J. Nucl. and Radiochem. Sci. 6, (2005) pp. A1-A19 (nucl-th/0503061).



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

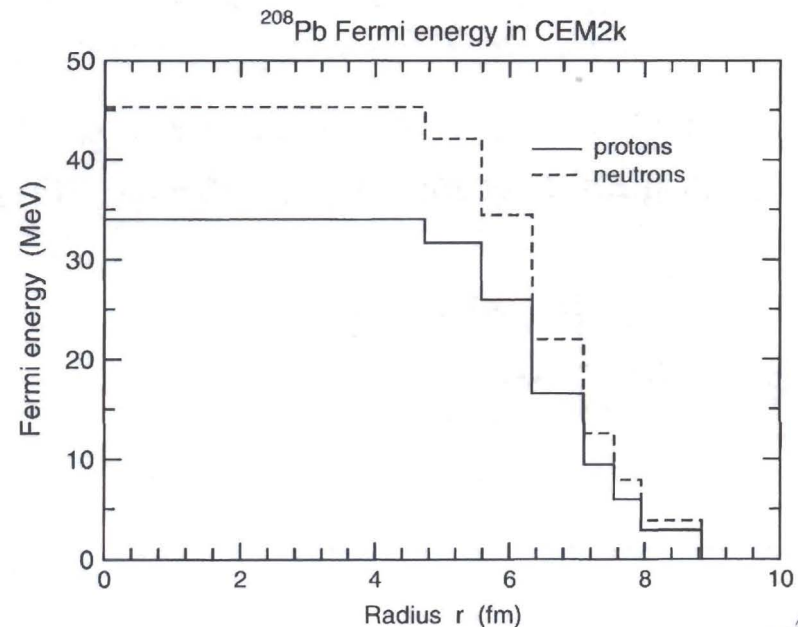
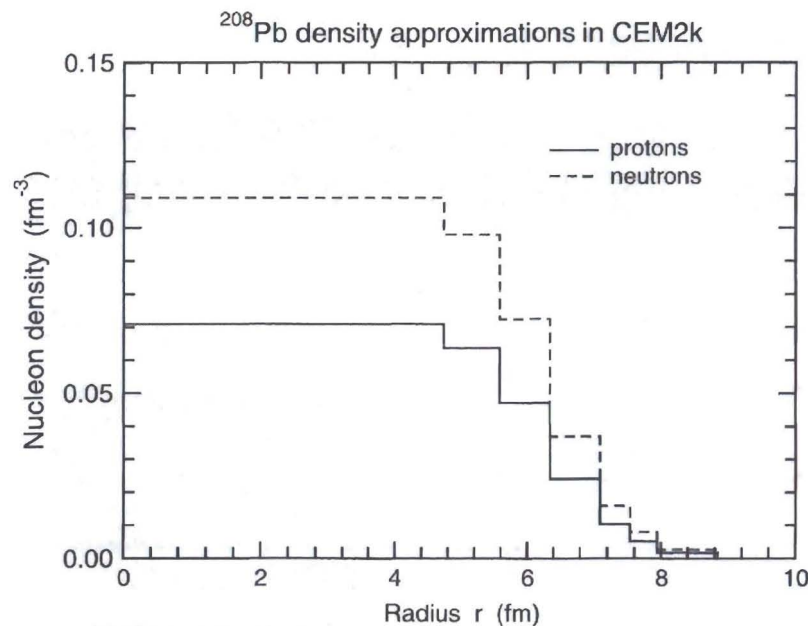
$$\rho(r) = \rho_p(r) + \rho_n(r) = \rho_0 \{1 + \exp[(r - c)/a]\}$$

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 $T_F(r) = \hbar^2[3\pi^2\rho(r)]^{2/3}/(2m_N)$





$$NN \rightarrow NN, \quad NN \rightarrow \pi NN, \quad NN \rightarrow \pi_1, \dots, \pi_i NN$$

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

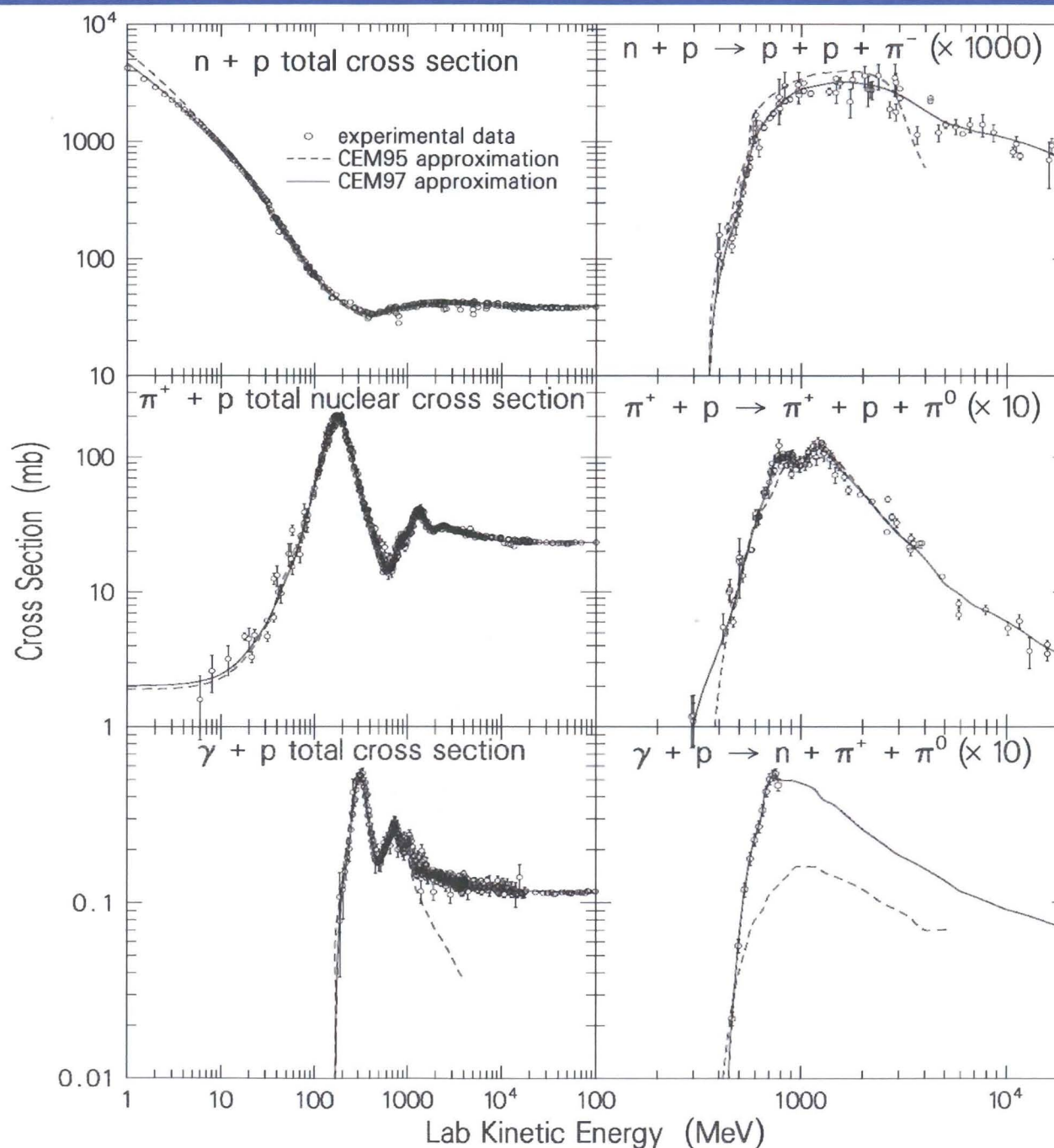
$$\pi NN \rightarrow NN$$

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

$$\begin{aligned} \gamma + p &\rightarrow p + \pi^0, \\ &\rightarrow n + \pi^+, \\ &\rightarrow p + \pi^+ + \pi^-, \\ &\rightarrow p + \pi^0 + \pi^0, \\ &\rightarrow n + \pi^+ + \pi^0. \end{aligned}$$

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

Pauli principle forbids a number of intranuclear collisions





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 ξ , 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 $N = M = 3$,

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

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 φ 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.

J. Cugnon, C. Volant, and S. Vuillier, Nucl. Phys. A620 (1997) 475;
A. Boudar, J. Cugnon, S. Leray, and C. Volant, Phys. Rev. C 66 (2002) 044615;
Th. Aoust and J. Cugnon, Eur. Phys. J. A21 (2004) 79;

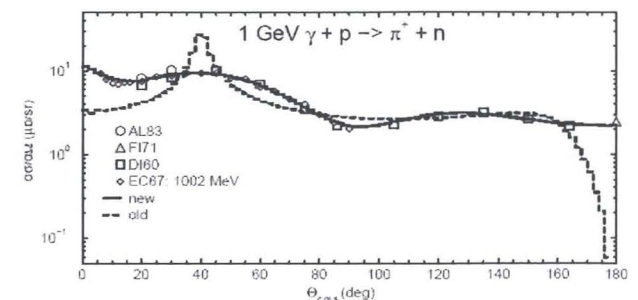
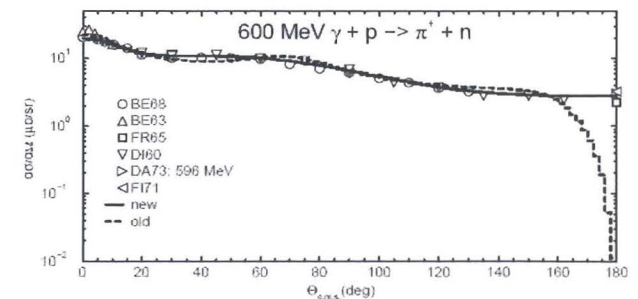
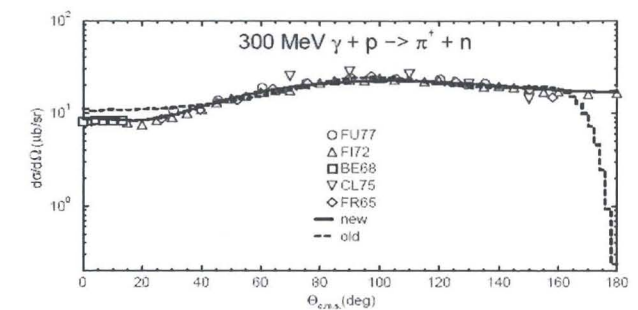
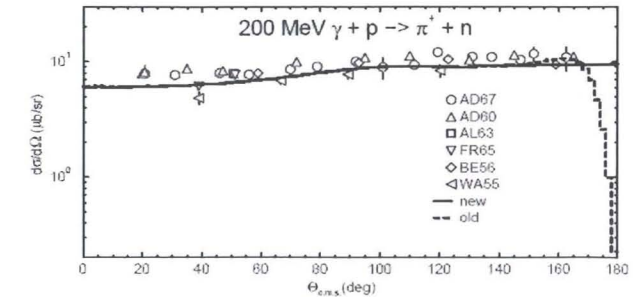
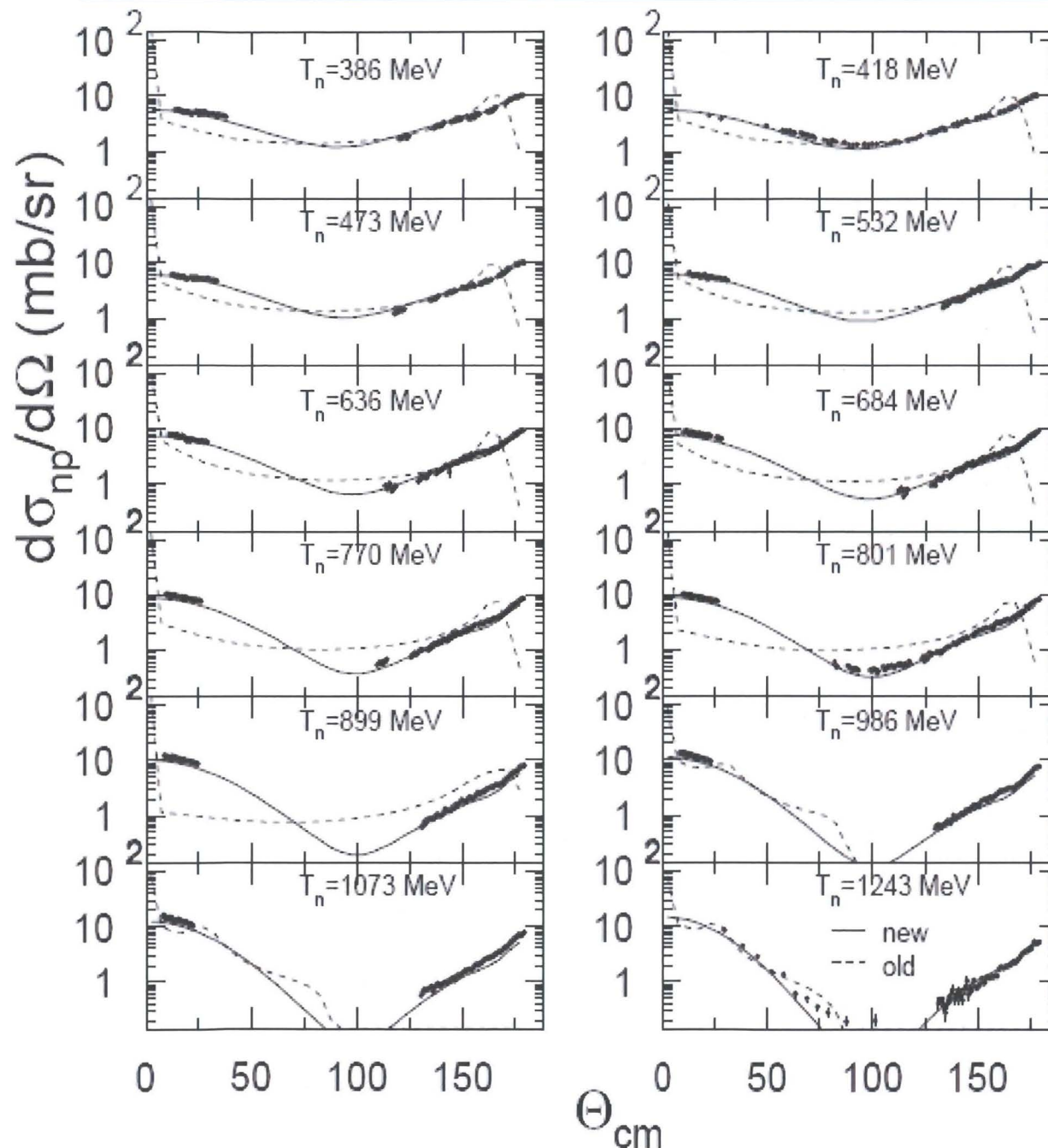
Helder Duarte, Proc ADTT'99, Praha, Czech Republic, June 7--11, 1999,
web page <http://fjfi.cvut.cz/con\adtt99>;
Proc. 10th Int. Conf. on Nuclear Reaction Mechanisms, Varenna, Italy, June 9-13,
2003; <http://lxmi.mi.infn.it/~gadioli/registered.htm>;
Phys. Rev. C 75 (2007) 024611.



Similarly, for γp and γn 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 Θ for any E_γ , using a single random number ζ uniformly distributed in the interval $[0,1]$.

A. S. Iljinov, I. A. Pshenichnov, N. Bianchi, E. De Sanctis,
B. V. Muccifora, M. Mirazita, and P. Rossi,
Nucl. Phys. A616 (1997) 575.





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:

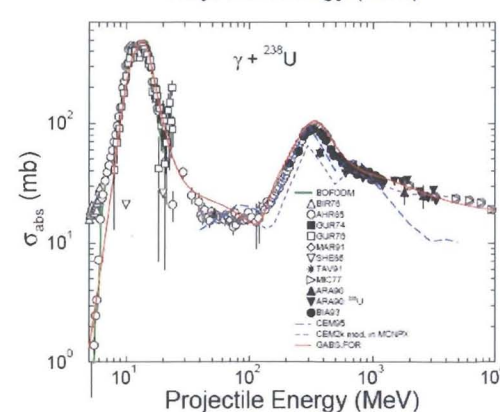
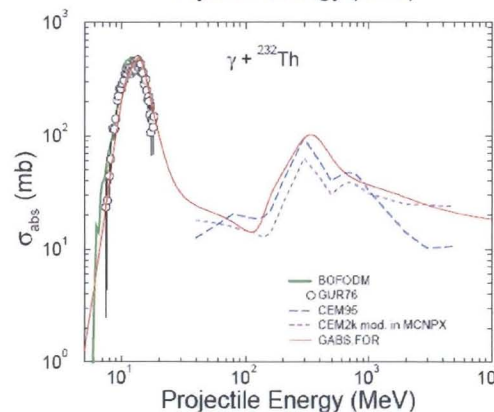
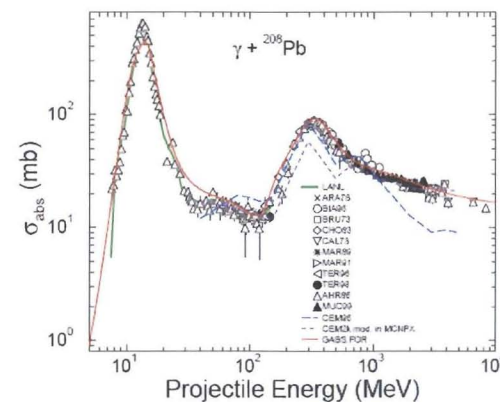
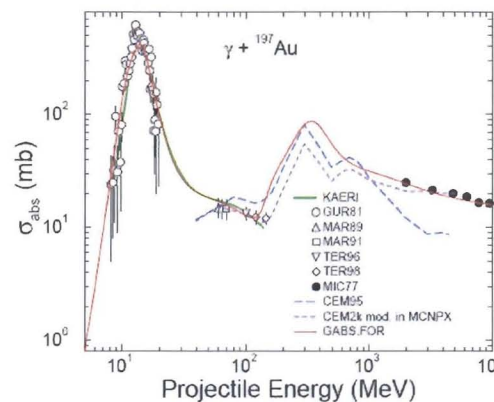
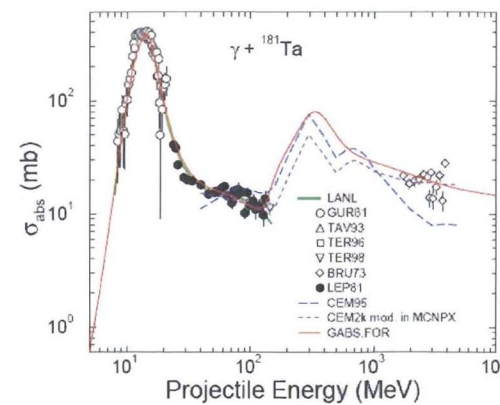
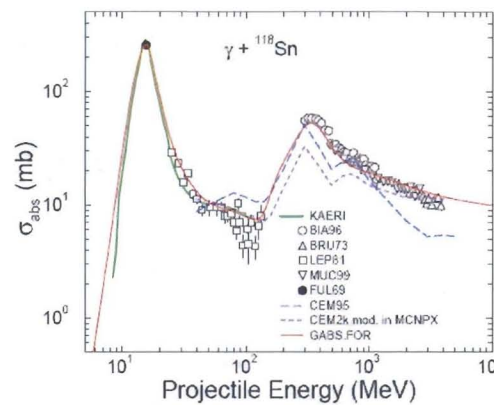
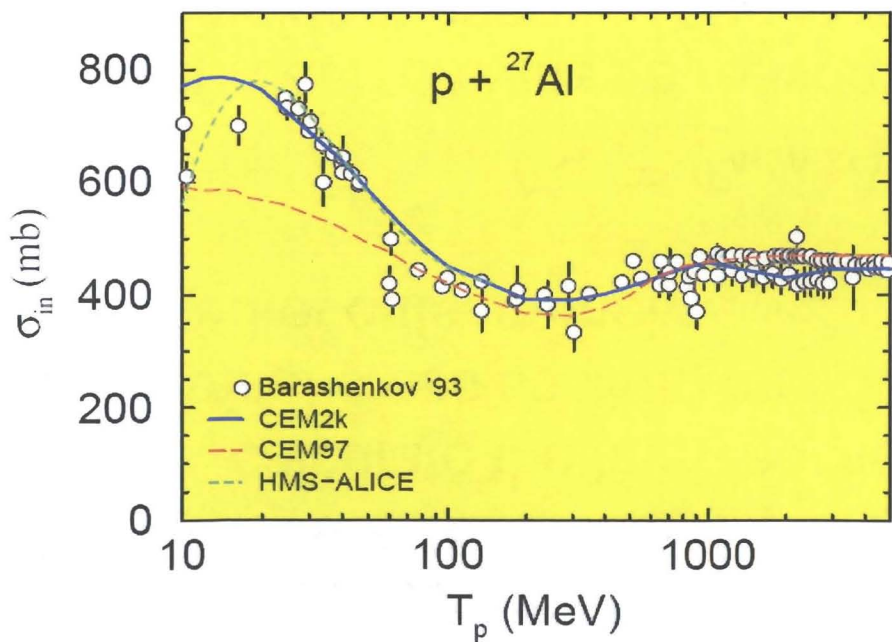
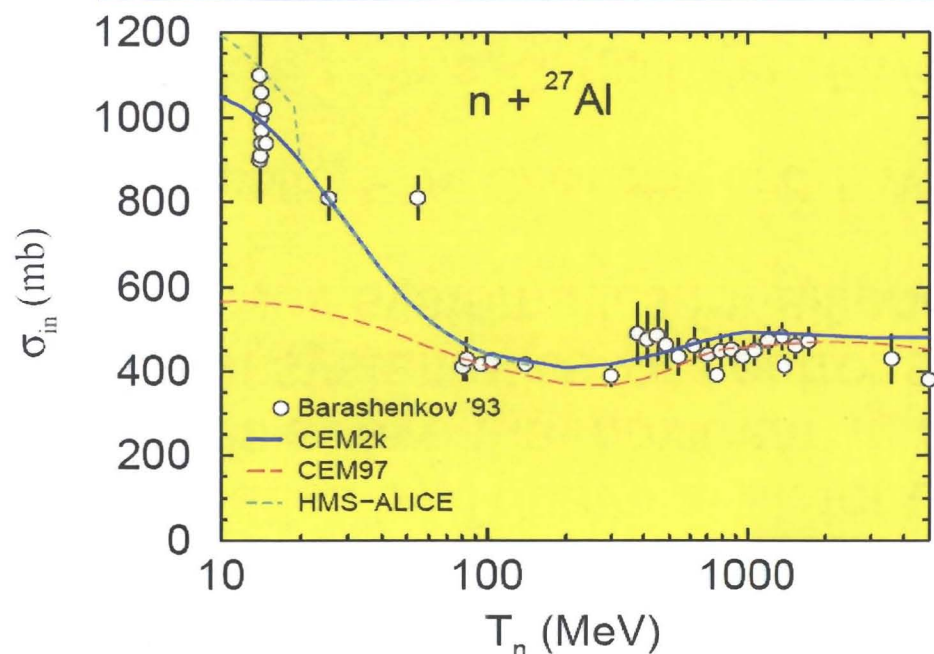
$$\sigma_{in} = \sigma_{geom} N_{in} / (N_{in} + N_{el}).$$

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:

R. K. Tripathi, F. A. Cucinotta, and J. W. Wilson, NIM B117 (1996) 347;

C. Kalbach, J. Phys. G: Nucl. Part. Phys. 24 (1998) 847:

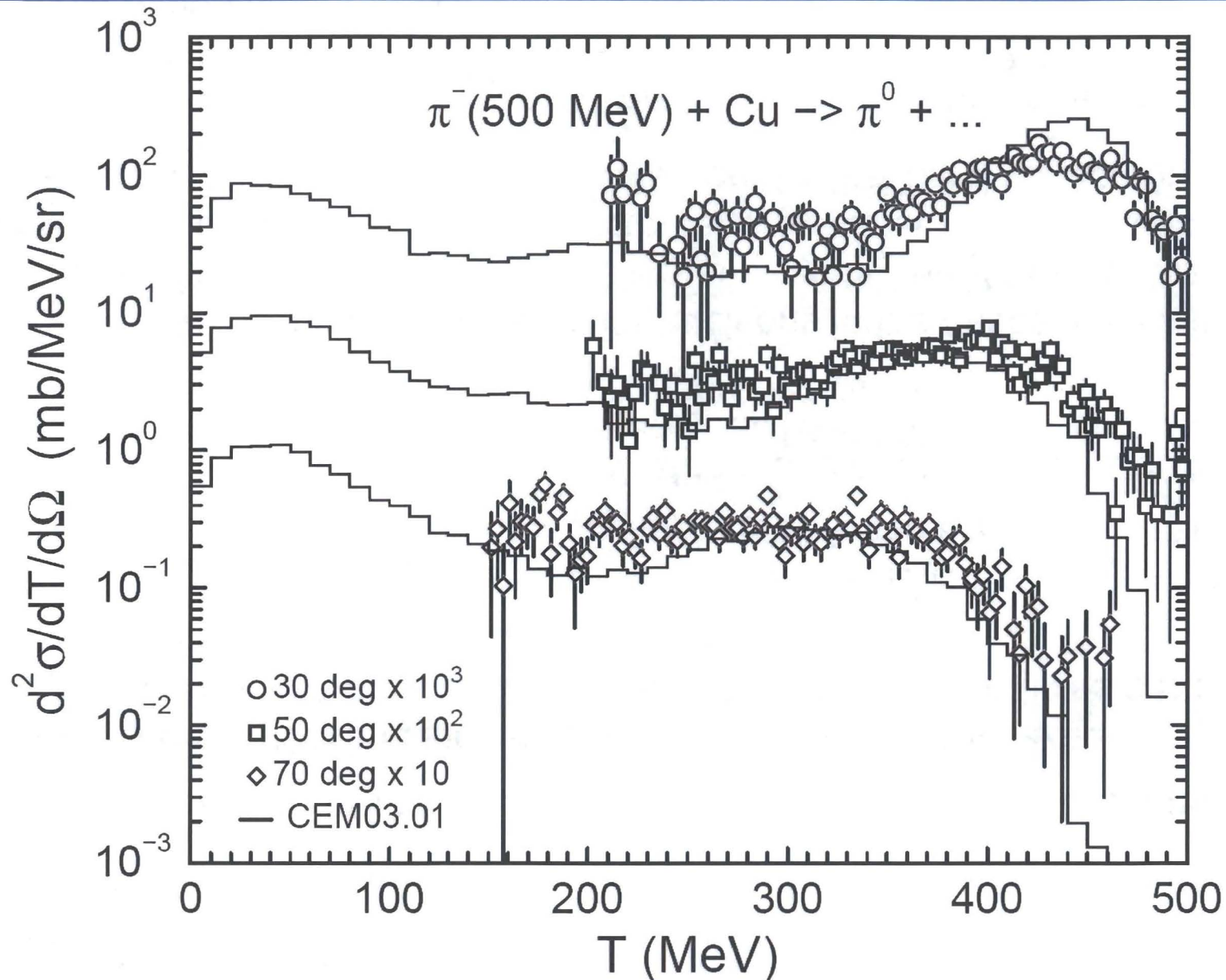
M. V. Kossov, Eur. Phys. J. A 14 (2002) 377.





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.



Exp. data (symbols): J. Ouyang, PhD thesis U. of Colorado, 1992; S. G. Mashnik,
R. J. Peterson, A. J. Sierk, M. R. Braunstein, Phys. Rev. C61 (2000) 034601



The **INC** stage of reactions is described by **LAQGSM03.03** with a recently improved version [1] of the time-dependent 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.

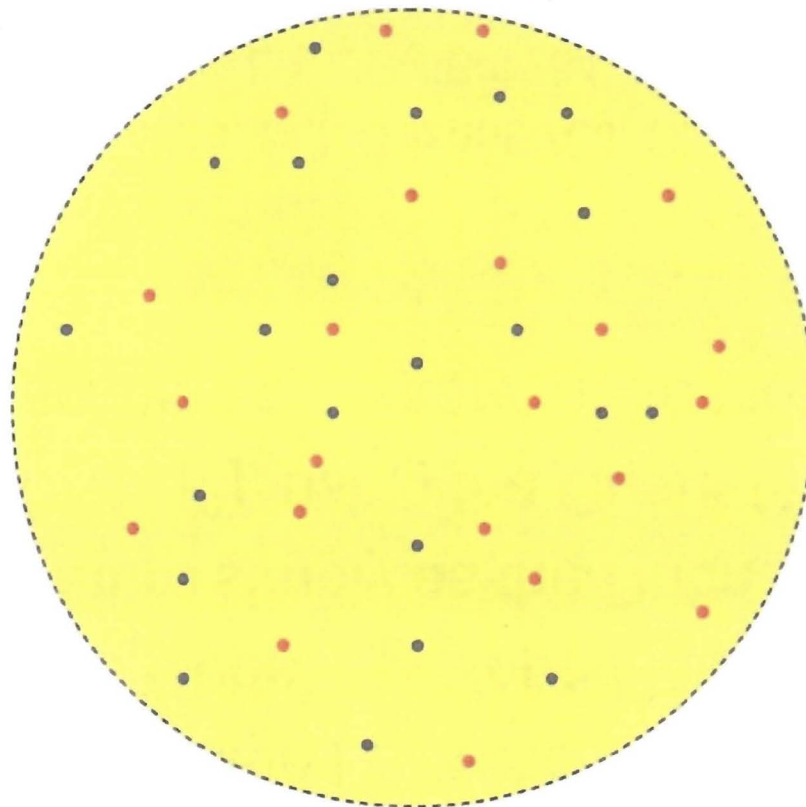
- [1] S.G. Mashnik, K.K. Gudima, M.I. Baznat, A.J. Sierk, R.A. Prael, N.V. Mokhov, LANL Report, LA-UR-06-1764, Los-Alamos (2006).
- [2] V.D. Toneev, K.K. Gudima, Nucl. Phys. A400 (1983) 173c.
- [3] N.S. Amelin, K.K. Gudima, V.D. Toneev, Sov. J. Nucl. Phys. 51 (1990) 327; ibid. 51 (1990) 1730; ibid. 52 (1990) 172;
N. S. Amelin, CERN/IT/ASD Report CERN/IT/99/6, Geneva, Switzerland (1999).



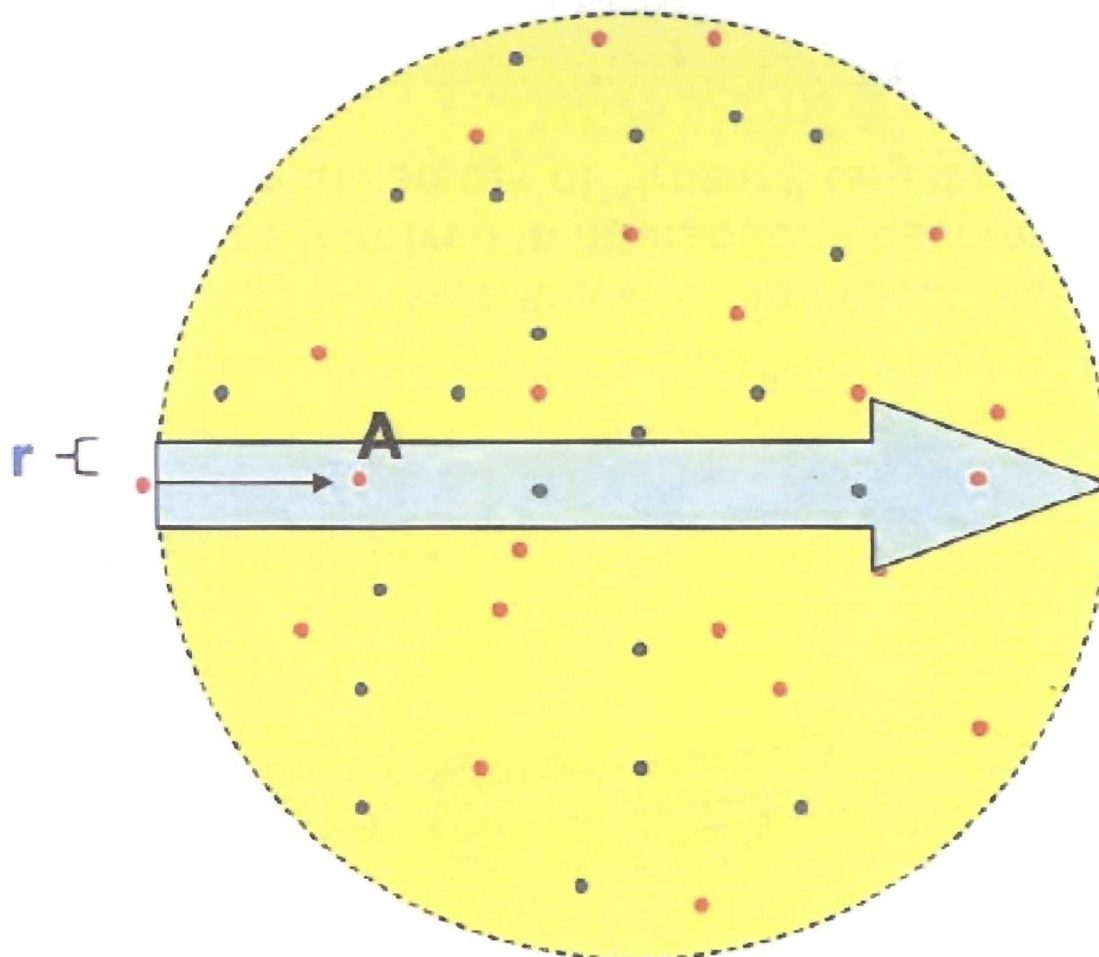
LAQGSM uses a continuous nuclear distribution (no “zones”)

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

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

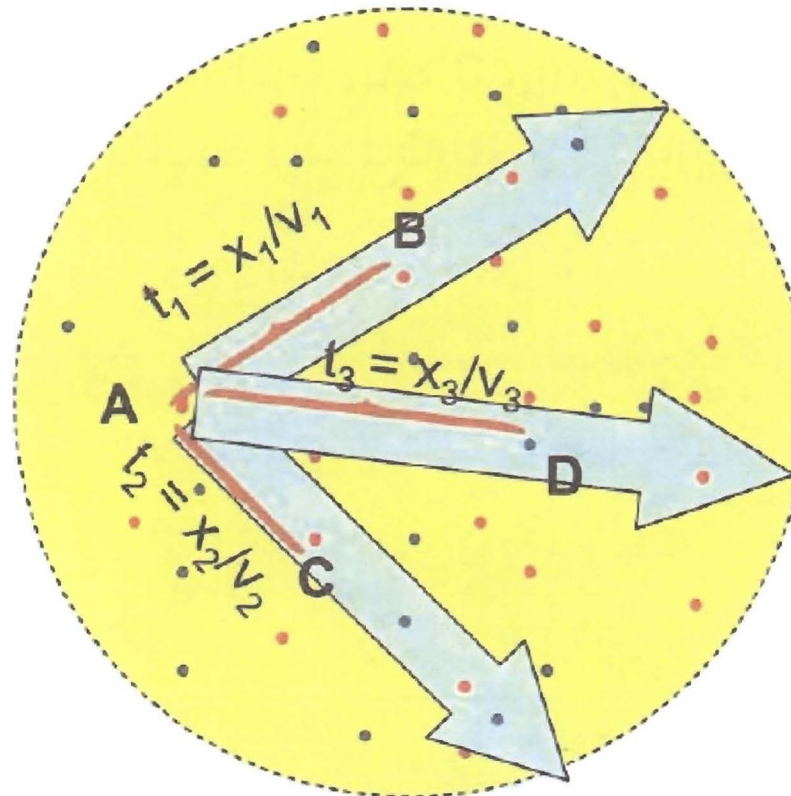


Before starting to simulate an INC event, position of all IntraNuclear nucleons are simulated and “frozen”



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



$t_{1(2,3,...)}^f$ is the **formation** time of the cascade particle #1(2,3,...)

If $t_2 < t_1$, $t_2 < t_3, \dots$, and $t_2 > t_2^f$, 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: $t^f = (E/m)t_f^0$; $t_f^0 = C_t \hbar/m_\pi$;

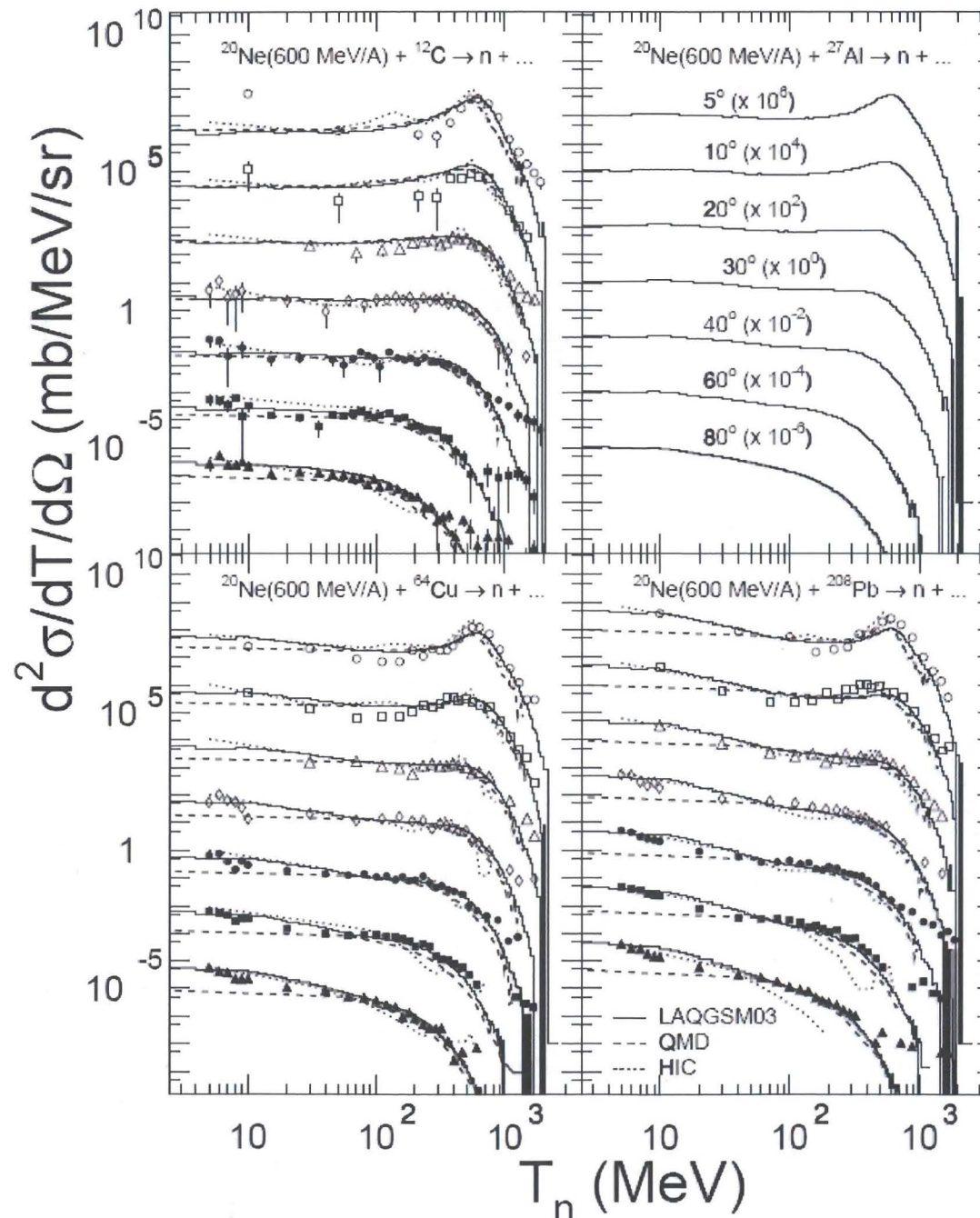
$C_t = 1.0$ for mesons and ~ 0.0 for baryons



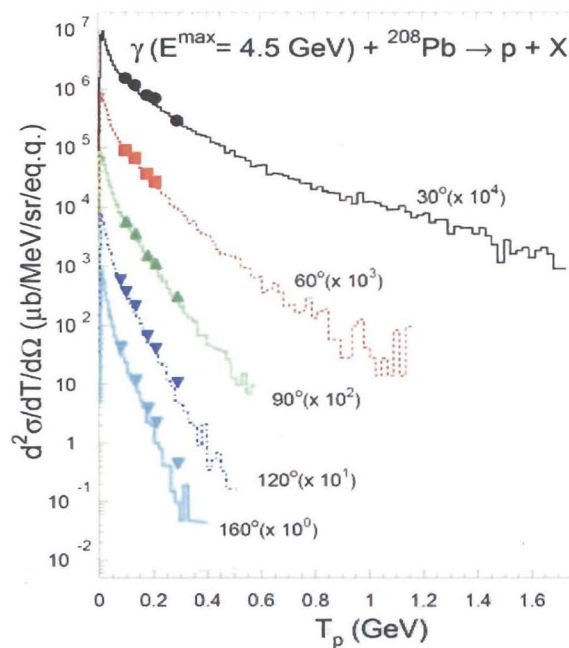
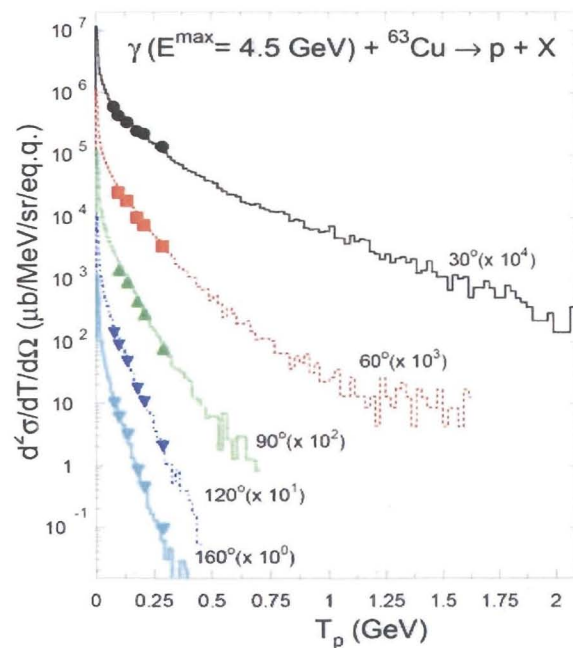
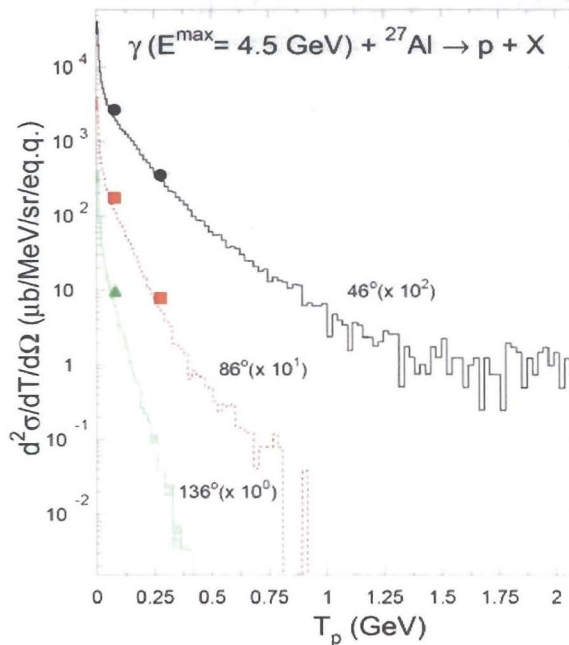
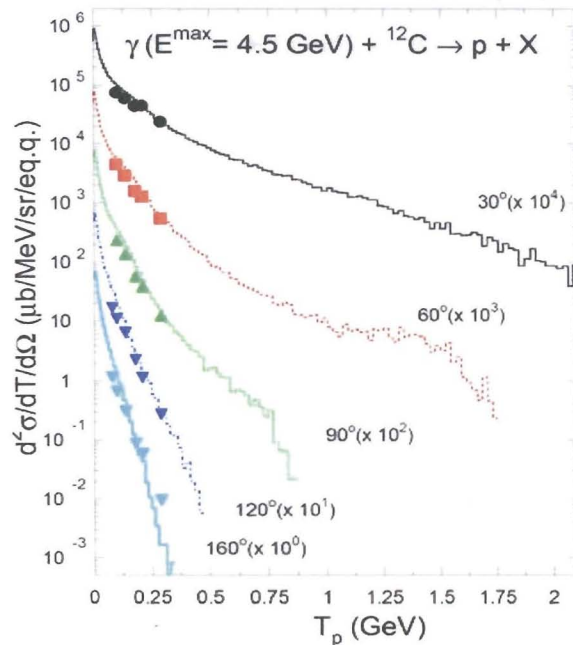
#	γp -interactions	γn -interactions
1	$\gamma p \rightarrow \pi^+ n$	$\gamma n \rightarrow \pi^- p$
2	$\gamma p \rightarrow \pi^0 n$	$\gamma n \rightarrow \pi^0 n$
3	$\gamma p \rightarrow \Delta^{++} \pi^-$	$\gamma n \rightarrow \Delta^+ \pi^-$
4	$\gamma p \rightarrow \Delta^+ \pi^0$	$\gamma n \rightarrow \Delta^0 \pi^0$
5	$\gamma p \rightarrow \Delta^0 \pi^+$	$\gamma n \rightarrow \Delta^- \pi^+$
6	$\gamma p \rightarrow \rho^0 p$	$\gamma n \rightarrow \rho^0 n$
7	$\gamma p \rightarrow \rho^+ n$	$\gamma n \rightarrow \rho^- p$
8	$\gamma p \rightarrow \eta p$	$\gamma n \rightarrow \eta n$
9	$\gamma p \rightarrow \omega p$	$\gamma n \rightarrow \omega n$
10	$\gamma p \rightarrow \Lambda K^+$	$\gamma n \rightarrow \Lambda K^0$
11	$\gamma p \rightarrow \Sigma^0 K^+$	$\gamma n \rightarrow \Sigma^0 K^0$
12	$\gamma p \rightarrow \Sigma^+ K^0$	$\gamma n \rightarrow \Sigma^- K^+$
13	$\gamma p \rightarrow \eta' p$	$\gamma n \rightarrow \eta' n$
14	$\gamma p \rightarrow \phi p$	$\gamma n \rightarrow \phi n$
15	$\gamma p \rightarrow \pi^+ \pi^- p$	$\gamma n \rightarrow \pi^+ \pi^- n$
16	$\gamma p \rightarrow \pi^0 \pi^+ n$	$\gamma n \rightarrow \pi^0 \pi^- p$
17	$\gamma p \rightarrow \pi^0 \pi^0 p$	$\gamma n \rightarrow \pi^0 \pi^0 n$
18	$\gamma p \rightarrow \pi^0 \pi^0 \pi^0 p$	$\gamma n \rightarrow \pi^0 \pi^0 \pi^0 n$
19	$\gamma p \rightarrow \pi^+ \pi^- \pi^0 p$	$\gamma n \rightarrow \pi^+ \pi^- \pi^0 n$
20	$\gamma p \rightarrow \pi^+ \pi^0 \pi^0 n$	$\gamma n \rightarrow \pi^- \pi^0 \pi^0 p$
21	$\gamma p \rightarrow \pi^+ \pi^+ \pi^- n$	$\gamma n \rightarrow \pi^+ \pi^- \pi^- p$
22	$\gamma p \rightarrow \pi^0 \pi^0 \pi^0 \pi^0 p$	$\gamma n \rightarrow \pi^0 \pi^0 \pi^0 \pi^0 n$
23	$\gamma p \rightarrow \pi^+ \pi^- \pi^0 \pi^0 p$	$\gamma n \rightarrow \pi^+ \pi^- \pi^0 \pi^0 n$
24	$\gamma p \rightarrow \pi^+ \pi^+ \pi^- \pi^- p$	$\gamma n \rightarrow \pi^+ \pi^+ \pi^- \pi^- n$
25	$\gamma p \rightarrow \pi^+ \pi^0 \pi^0 \pi^0 n$	$\gamma n \rightarrow \pi^- \pi^0 \pi^0 \pi^0 p$
26	$\gamma p \rightarrow \pi^+ \pi^+ \pi^- \pi^0 n$	$\gamma n \rightarrow \pi^+ \pi^- \pi^- \pi^0 p$
27	$\gamma p \rightarrow \pi^0 \pi^0 \pi^0 \pi^0 \pi^0 p$	$\gamma n \rightarrow \pi^0 \pi^0 \pi^0 \pi^0 \pi^0 n$
28	$\gamma p \rightarrow \pi^+ \pi^- \pi^0 \pi^0 \pi^0 p$	$\gamma n \rightarrow \pi^+ \pi^- \pi^0 \pi^0 \pi^0 n$
29	$\gamma p \rightarrow \pi^+ \pi^+ \pi^- \pi^- \pi^0 p$	$\gamma n \rightarrow \pi^+ \pi^+ \pi^- \pi^- \pi^0 n$
30	$\gamma p \rightarrow \pi^+ \pi^0 \pi^0 \pi^0 \pi^0 n$	$\gamma n \rightarrow \pi^- \pi^0 \pi^0 \pi^0 \pi^0 p$
31	$\gamma p \rightarrow \pi^+ \pi^+ \pi^- \pi^0 \pi^0 n$	$\gamma n \rightarrow \pi^+ \pi^- \pi^- \pi^0 \pi^0 p$
32	$\gamma p \rightarrow \pi^+ \pi^+ \pi^+ \pi^- \pi^- n$	$\gamma n \rightarrow \pi^+ \pi^+ \pi^- \pi^- \pi^- p$

#	γp -interactions	γn -interactions
33	$\gamma p \rightarrow \pi^0 \pi^0 \pi^0 \pi^0 \pi^0 p$	$\gamma n \rightarrow \pi^0 \pi^0 \pi^0 \pi^0 \pi^0 n$
34	$\gamma p \rightarrow \pi^+ \pi^- \pi^0 \pi^0 \pi^0 p$	$\gamma n \rightarrow \pi^+ \pi^- \pi^0 \pi^0 \pi^0 n$
35	$\gamma p \rightarrow \pi^+ \pi^+ \pi^- \pi^- \pi^0 p$	$\gamma n \rightarrow \pi^+ \pi^+ \pi^- \pi^- \pi^0 n$
36	$\gamma p \rightarrow \pi^+ \pi^+ \pi^+ \pi^- \pi^- p$	$\gamma n \rightarrow \pi^+ \pi^+ \pi^+ \pi^- \pi^- n$
37	$\gamma p \rightarrow \pi^+ \pi^0 \pi^0 \pi^0 \pi^0 n$	$\gamma n \rightarrow \pi^- \pi^0 \pi^0 \pi^0 \pi^0 p$
38	$\gamma p \rightarrow \pi^+ \pi^+ \pi^- \pi^0 \pi^0 n$	$\gamma n \rightarrow \pi^+ \pi^- \pi^- \pi^0 \pi^0 p$
39	$\gamma p \rightarrow \pi^+ \pi^+ \pi^+ \pi^- \pi^- n$	$\gamma n \rightarrow \pi^+ \pi^+ \pi^- \pi^- \pi^- p$
40	$\gamma p \rightarrow \pi^0 \pi^0 \pi^0 \pi^0 \pi^0 \pi^0 p$	$\gamma n \rightarrow \pi^0 \pi^0 \pi^0 \pi^0 \pi^0 \pi^0 n$
41	$\gamma p \rightarrow \pi^+ \pi^- \pi^0 \pi^0 \pi^0 \pi^0 p$	$\gamma n \rightarrow \pi^+ \pi^- \pi^0 \pi^0 \pi^0 \pi^0 n$
42	$\gamma p \rightarrow \pi^+ \pi^+ \pi^- \pi^- \pi^0 \pi^0 p$	$\gamma n \rightarrow \pi^+ \pi^+ \pi^- \pi^- \pi^0 \pi^0 n$
43	$\gamma p \rightarrow \pi^+ \pi^+ \pi^+ \pi^- \pi^- \pi^0 p$	$\gamma n \rightarrow \pi^+ \pi^+ \pi^+ \pi^- \pi^- \pi^0 n$
44	$\gamma p \rightarrow \pi^+ \pi^0 \pi^0 \pi^0 \pi^0 \pi^0 n$	$\gamma n \rightarrow \pi^- \pi^0 \pi^0 \pi^0 \pi^0 \pi^0 p$
45	$\gamma p \rightarrow \pi^+ \pi^+ \pi^- \pi^0 \pi^0 \pi^0 n$	$\gamma n \rightarrow \pi^+ \pi^- \pi^- \pi^0 \pi^0 \pi^0 p$
46	$\gamma p \rightarrow \pi^+ \pi^+ \pi^+ \pi^- \pi^- \pi^0 n$	$\gamma n \rightarrow \pi^+ \pi^+ \pi^- \pi^- \pi^- \pi^0 p$
47	$\gamma p \rightarrow \pi^+ \pi^+ \pi^+ \pi^+ \pi^- \pi^- n$	$\gamma n \rightarrow \pi^+ \pi^+ \pi^+ \pi^- \pi^- \pi^- p$
48	$\gamma p \rightarrow \pi^0 \pi^0 \pi^0 \pi^0 \pi^0 \pi^0 \pi^0 p$	$\gamma n \rightarrow \pi^0 \pi^0 \pi^0 \pi^0 \pi^0 \pi^0 \pi^0 n$
49	$\gamma p \rightarrow \pi^+ \pi^- \pi^0 \pi^0 \pi^0 \pi^0 \pi^0 p$	$\gamma n \rightarrow \pi^+ \pi^- \pi^0 \pi^0 \pi^0 \pi^0 \pi^0 n$
50	$\gamma p \rightarrow \pi^+ \pi^+ \pi^- \pi^- \pi^0 \pi^0 \pi^0 p$	$\gamma n \rightarrow \pi^+ \pi^+ \pi^- \pi^- \pi^0 \pi^0 \pi^0 n$
51	$\gamma p \rightarrow \pi^+ \pi^+ \pi^+ \pi^- \pi^- \pi^0 \pi^0 p$	$\gamma n \rightarrow \pi^+ \pi^+ \pi^+ \pi^- \pi^- \pi^0 \pi^0 n$
52	$\gamma p \rightarrow \pi^+ \pi^+ \pi^+ \pi^+ \pi^- \pi^- \pi^- p$	$\gamma n \rightarrow \pi^+ \pi^+ \pi^+ \pi^+ \pi^- \pi^- \pi^- n$
53	$\gamma p \rightarrow \pi^+ \pi^0 \pi^0 \pi^0 \pi^0 \pi^0 \pi^0 n$	$\gamma n \rightarrow \pi^- \pi^0 \pi^0 \pi^0 \pi^0 \pi^0 \pi^0 p$
54	$\gamma p \rightarrow \pi^+ \pi^+ \pi^- \pi^0 \pi^0 \pi^0 \pi^0 n$	$\gamma n \rightarrow \pi^+ \pi^- \pi^- \pi^0 \pi^0 \pi^0 \pi^0 p$
55	$\gamma p \rightarrow \pi^+ \pi^+ \pi^+ \pi^- \pi^- \pi^0 \pi^0 n$	$\gamma n \rightarrow \pi^+ \pi^+ \pi^- \pi^- \pi^- \pi^0 \pi^0 p$
56	$\gamma p \rightarrow \pi^+ \pi^+ \pi^+ \pi^+ \pi^- \pi^- \pi^0 n$	$\gamma n \rightarrow \pi^+ \pi^+ \pi^+ \pi^- \pi^- \pi^- \pi^0 p$

New approximations for γp and γn 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



Proc. ND2004:
Hiroshi Iwase,
Yoshiyuki Iwata,
Takashi Nakamura,
Konstantin Gudima,
Stepan Mashnik,
Arnold Sierk,
Richard Prael,
AIP Conf. Proc.
769 (2005) 1066-1069
(nucl-th/0501066)



Experimental data:

K. V. Alanakyan *et al.*,
Sov. J. Nucl. Phys.

25 (1977) 292; 34 (1981) 828;
Nucl. Phys. A367 (1981) 429

LAQGS03.03 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 ${}^4\text{He}$ by fitting them to measured data on various
reactions and have fixed several bugs observed in the original version [1].

[1] V. D. Toneev and K. K. Gudima, Nucl. Phys. **A400** (1983) 173c.

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

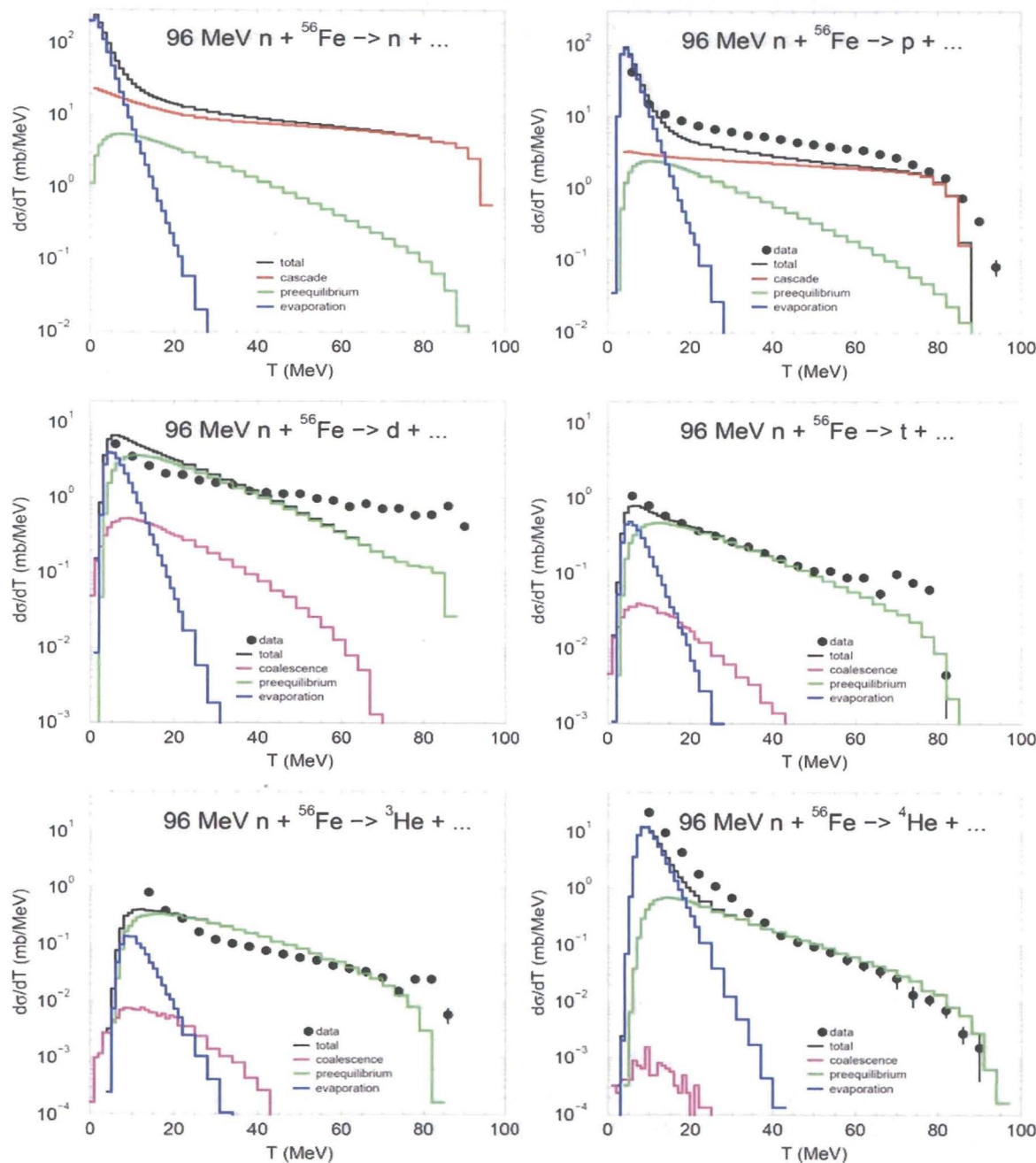
LAQGSM:

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

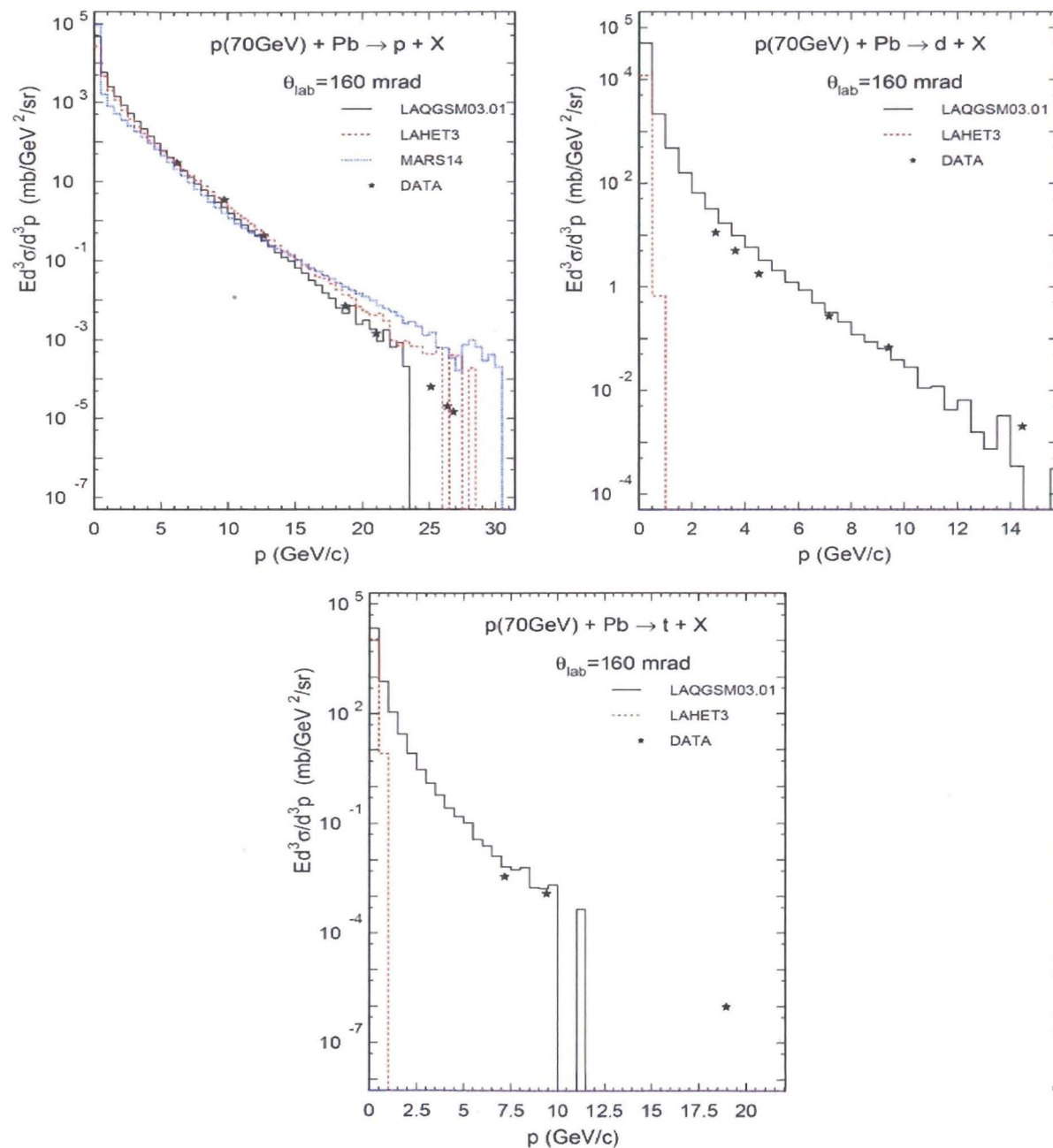
CEM:

$$p_c(d) = 150 \text{ MeV/c}; p_c(t) = P_c({}^3\text{He}) = 175 \text{ MeV/c}; p_c({}^4\text{He}) = 175 \text{ MeV/c}$$

Invited Seminar, Nuclear Theory Group, IPHC, Strasbourg, France, October 21, 2008, S. G. Mashnik, LA-UR-08-xxxx



Data: V. Blideanu *et al.*,
Phys. Rev. C 70 (2004) 014607



Data: L. M. Barkov *et al.*,
Sov. J. Nucl. Phys.
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]:

- [1] S.G. Mashnik, K.K. Gudima, A.J. Sierk, M.I. Baznat, N.V. Mokhov, "CEM03.01 User Manual," LANL Report LA-UR-05-7321, Los Alamos (2005); RSICC Code Package PSR-532, <http://www-rsicc.ornl.gov/codes/psr/psr5/psr-532.html> (2006).
- [2] K. K. Gudima, G. A. Ososkov, and V. D. Toneev, "Model for Pre-Equilibrium Decay of Excited Nuclei," Sov. J. Nucl. Phys. 21 (1975) 138.
- [3] S. G. Mashnik and V. D. Toneev, "MODEX - the Program for Calculation of the Energy Spectra of Particles Emitted in the Reactions of Pre-Equilibrium and Equilibrium Statistical Decays," JINR Communication P4-8417, Dubna (1974).
- [4] K. K. Gudima, S. G. Mashnik, and V. D. Toneev, "Cascade-Exciton Model of Nuclear Reactions: Model Formulation," Nucl. Phys. A401 (1983) 329.



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 , ^3He , and ^4He .

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

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

$$\lambda_c^j(p, h, E, T) = \frac{2s_j + 1}{\pi^2 \hbar^3} \mu_j \Re_j(p, h) \frac{\omega(p-1, h, E-B_j-T)}{\omega(p, h, E)} T \sigma_{inv}(T)$$



CEM considers the possibility of fast d, t, ^3He , and ^4He 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 ^4He 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 γ_j forming a complex particle which can be emitted during the preequilibrium state. The “condensation” probability γ_j is estimated in those references as the overlap integral of the wave function of independent nucleons with that of the complex particle (cluster)

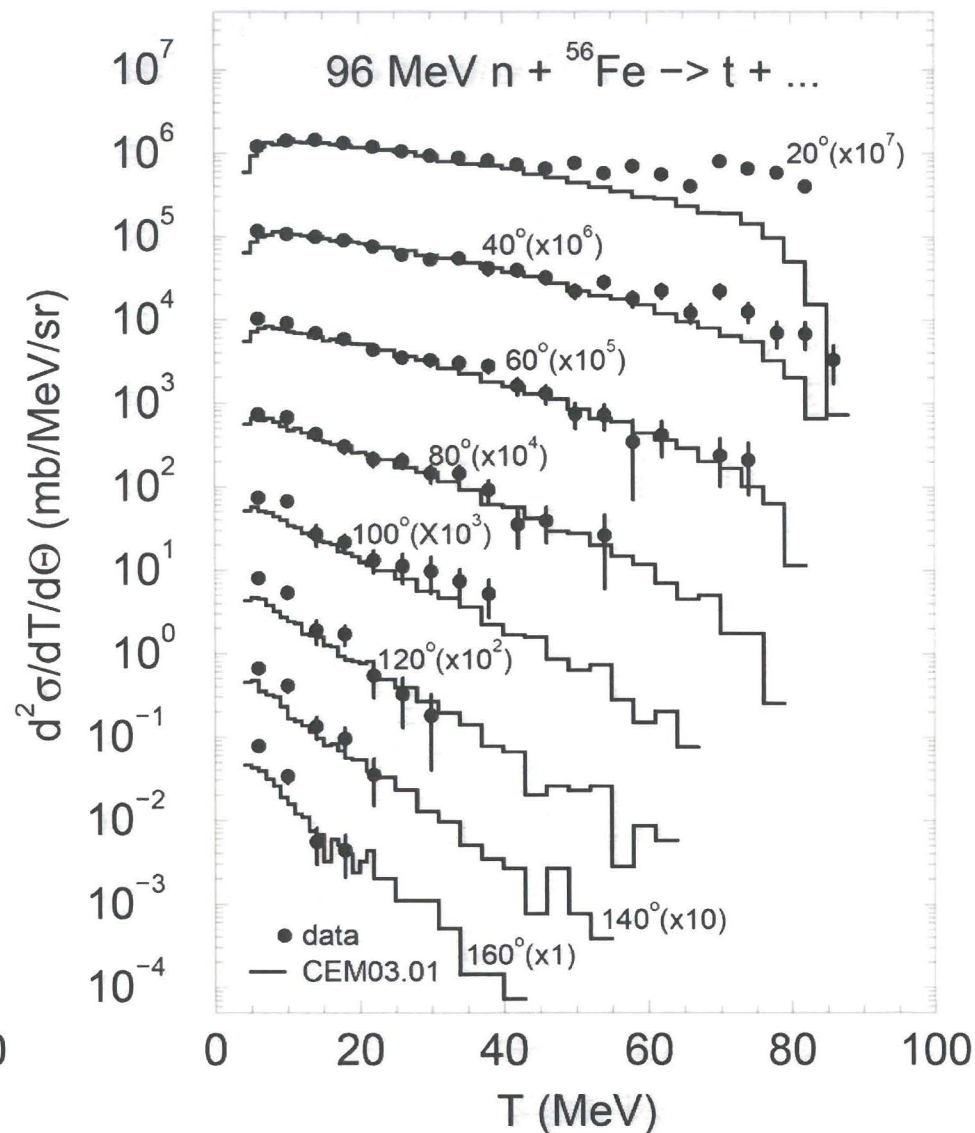
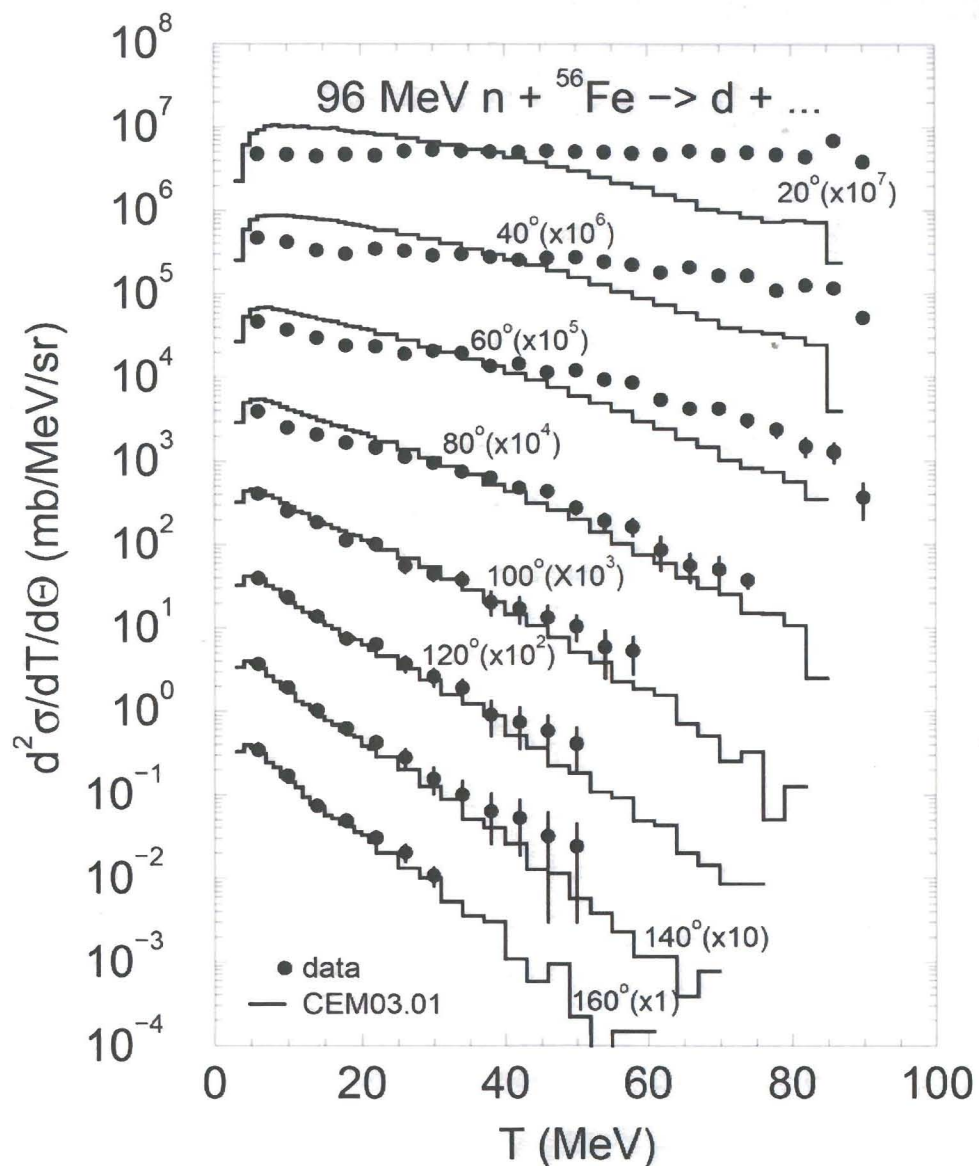
$$\gamma_j \simeq p_j^3 (V_j/V)^{p_j-1} = p_j^3 (p_j/A)^{p_j-1} .$$

This is a rather crude estimate. In the usual way the values γ_j are taken from fitting the theoretical preequilibrium spectra to the experimental ones. In CEM03.01, we fitted γ_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.



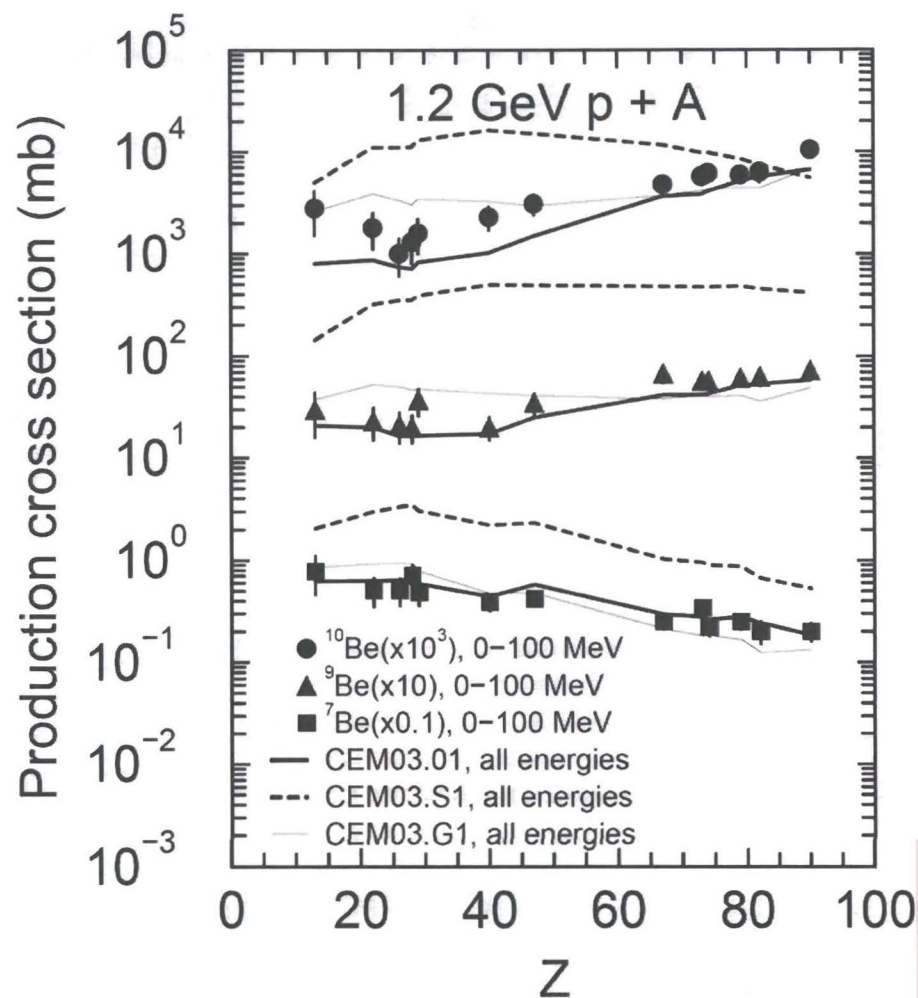
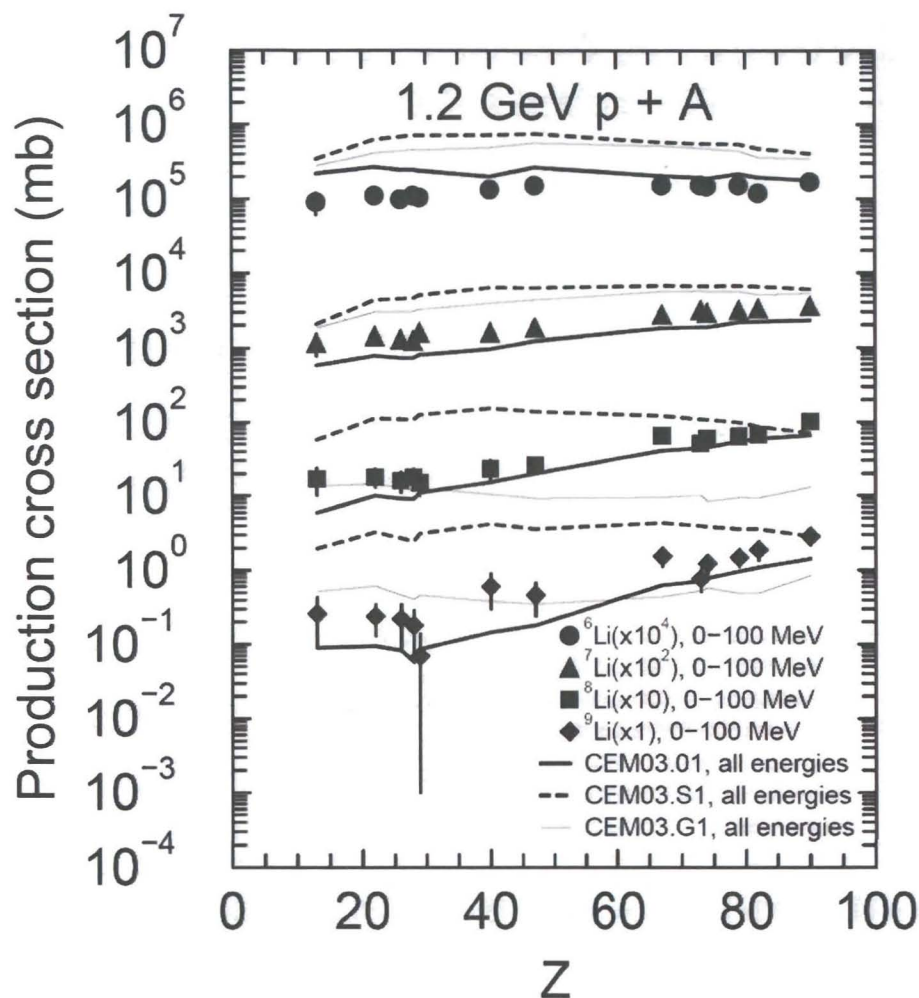
Experimental data: V. Blideanu *et al.*, Phys. Rev. C 70 (2004) 014607



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).

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

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



NESSI data: C.-M. Herbach *et al.*, Nucl. Phys. A765 (2006) 426-463



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

$$P_f = \frac{\Gamma_f}{\Gamma_f + \Gamma_n} = \frac{1}{1 + \Gamma_n/\Gamma_f}$$

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

$$s_n (= 2\sqrt{a_n(E - Q_n - \delta)}) \quad a_n = (A_i - 1)/8 \quad J_1 = \frac{(2s_n^2 - 6s_n + 6)e^{s_n} + s_n^2 - 6}{8a_n^2}$$

$$\Gamma_f = \frac{(s_f - 1)e^{s_f} + 1}{a_f}, \quad a_f = a_n \left(1.08926 + 0.01098(\chi - 31.08551)^2 \right), \text{ and } \chi = Z^2/A.$$

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



$$2) Z_j \geq 89$$

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

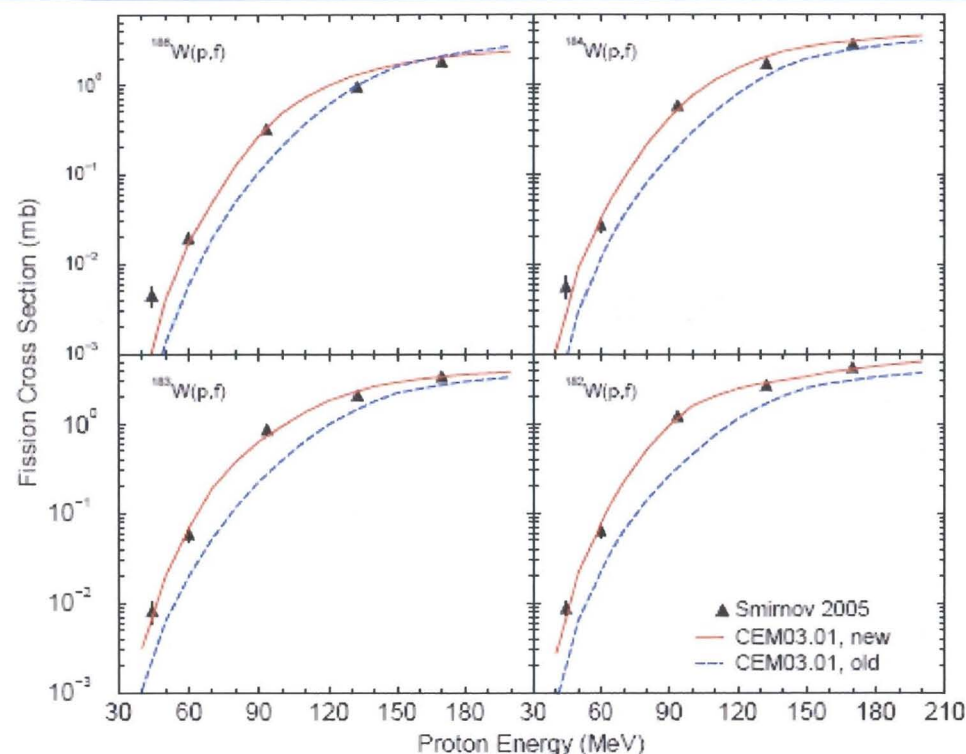
$C(Z)$ and $A_0(Z)$ are constants

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

$$a_f \rightarrow C_a \times a_f$$

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

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



S. G. Mashnik, A. J. Sierk,
K. K. Gudima, M. I. Baznat,
Proc. NPDC19, Journal of
Physics: Conference
Series, 41 (2006) 340-351
(nucl-th/0510070)

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

For nuclei with $Z_i^2/A_i > 35$,

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

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 σ_M as described below.

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

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



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

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

where

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

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

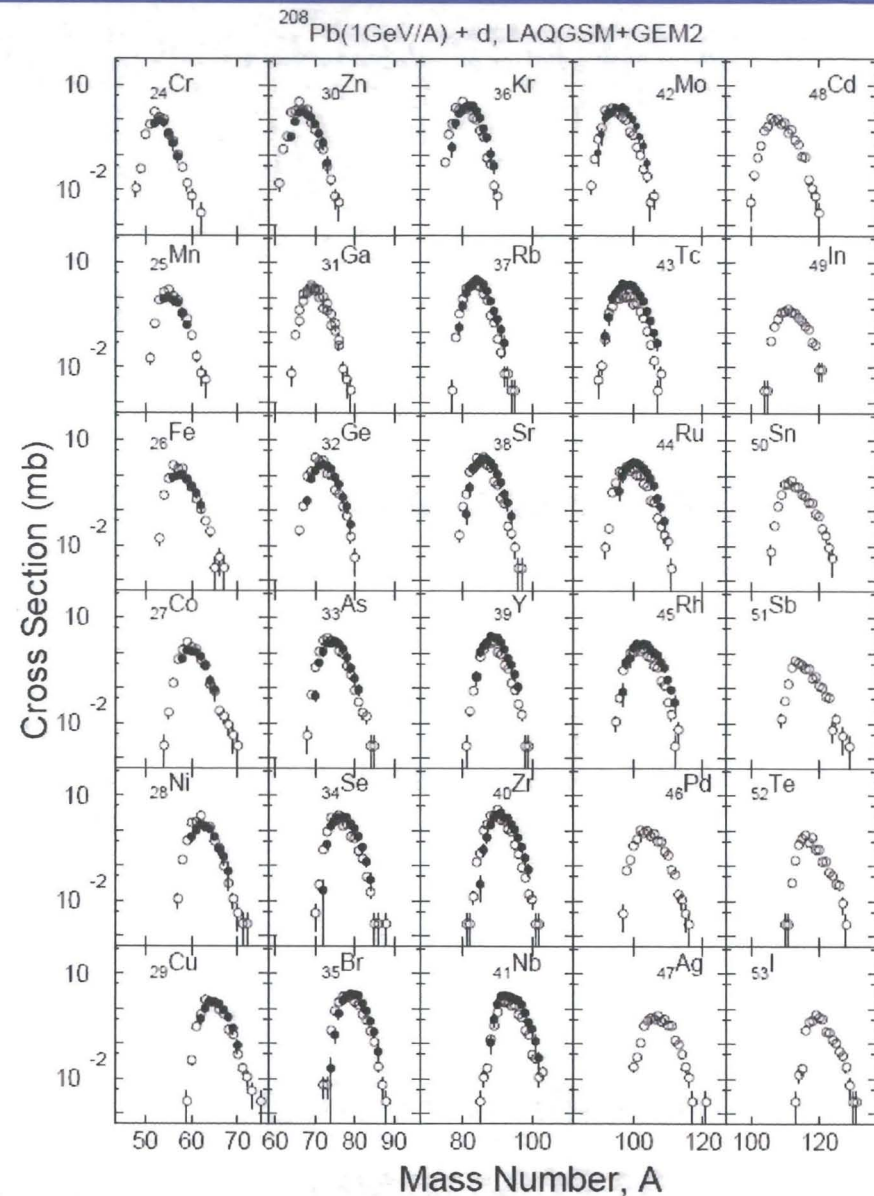
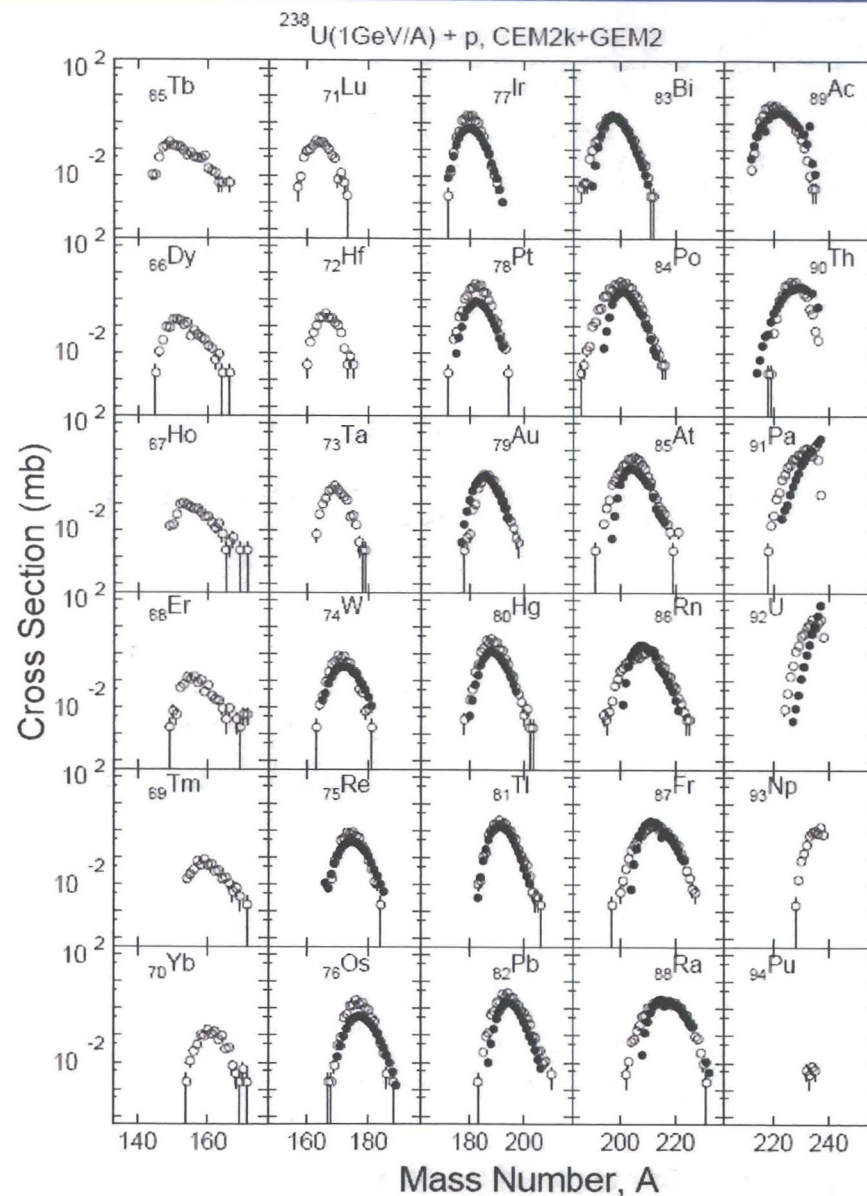
2.5.4. Kinetic Energy Distribution. The kinetic energy of fission fragments [MeV] is determined by a Gaussian distribution with mean ϵ_f and width σ_{ϵ_f} .

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

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

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

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



GSI data (filled circles): M. Bernas *et al.*, Nucl. Phys. **A725** (2003) 213;
T. Enqvist *et al.*, Nucl. Phys. **A703** (2003) 435; LAQGSM results: open circles



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].

[1] N. Amelin, “Physics and Algorithms of the Hadronic Monte-Carlo Event Generators. Notes for a Developer,” CERN/IT/ASD Report CERN/IT/99/6, Geneva, Switzerland (1999); “GEANT4, Users' Documents, Physics Reference Manual,” last update: 08/04/1999; <http://wwwinfo.cern.ch/asd/geant4/G4UsersDocuments/UsersGuides/PhysicsReferenceManual/html/PhysicsReferenceManual.html/>.

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

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

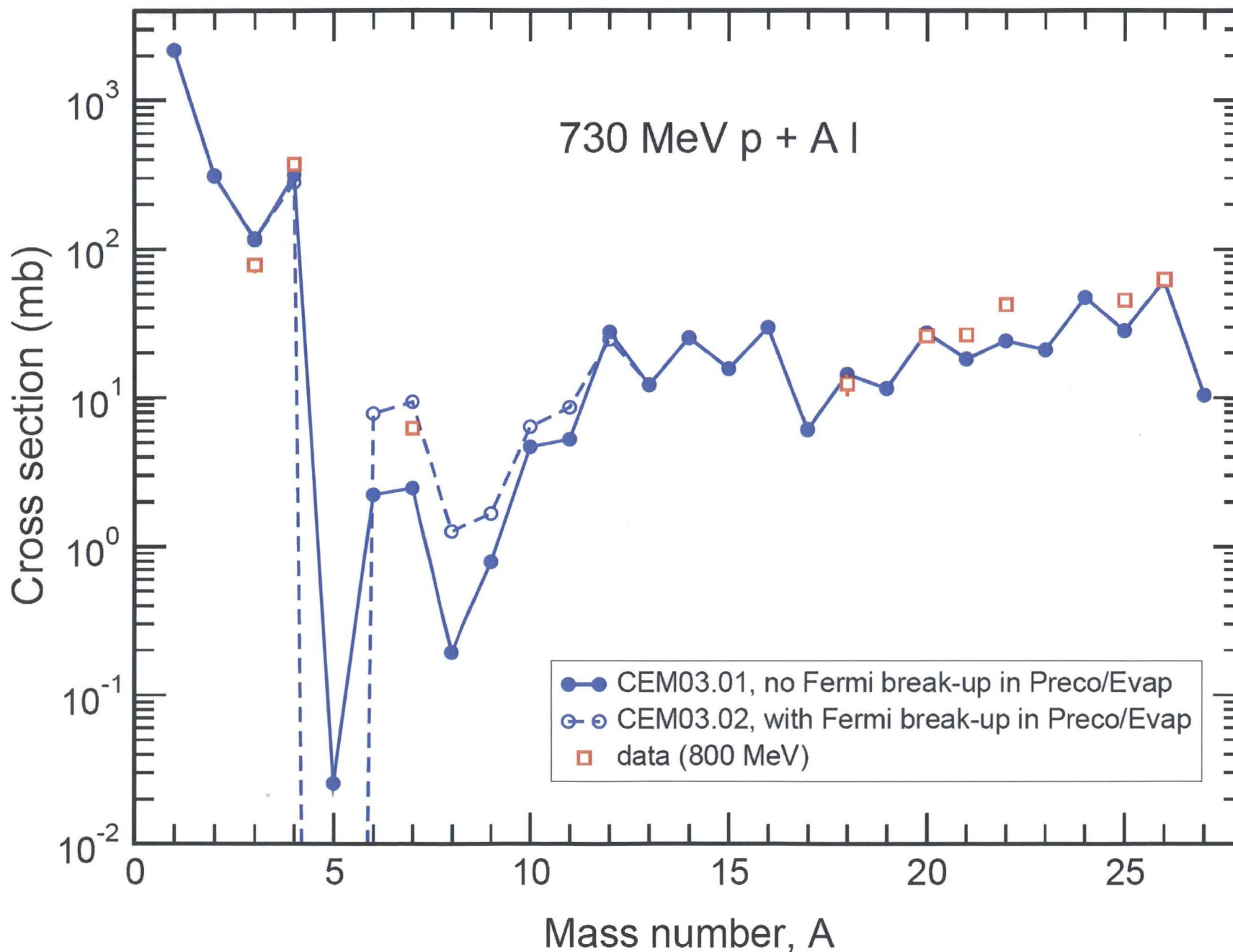
$$V = 4\pi R^3/3 = 4\pi r_0^3 A/3,$$

where $r_0 = 1.4$ 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 ${}^5\text{He}$, ${}^5\text{Li}$, ${}^8\text{Be}$, ${}^9\text{B}$, *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” xn and yp 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).



Invited Seminar, Nuclear Theory Group, IPHC, Strasbourg, France, October 21, 2008, S. G. Mashnik, LA-UR-08-xxxx

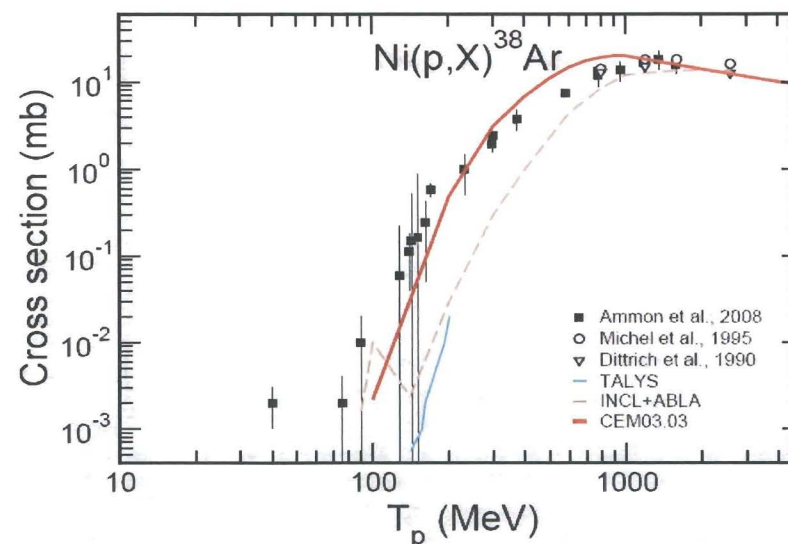
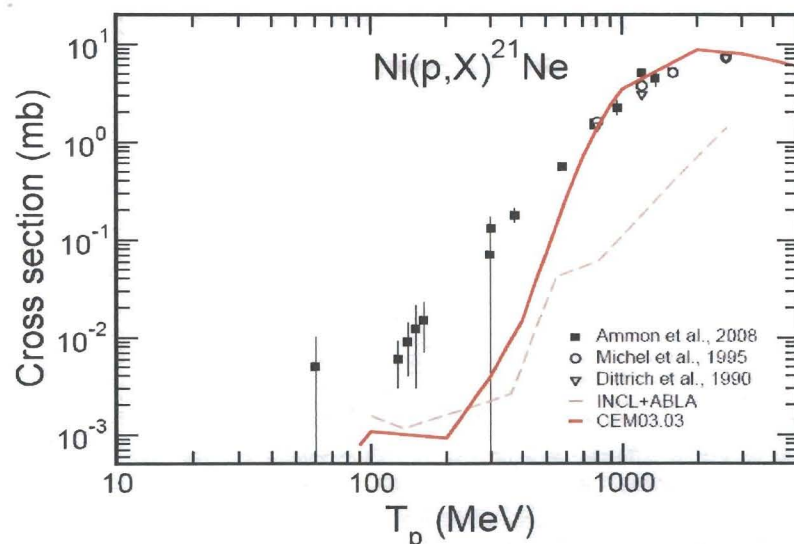
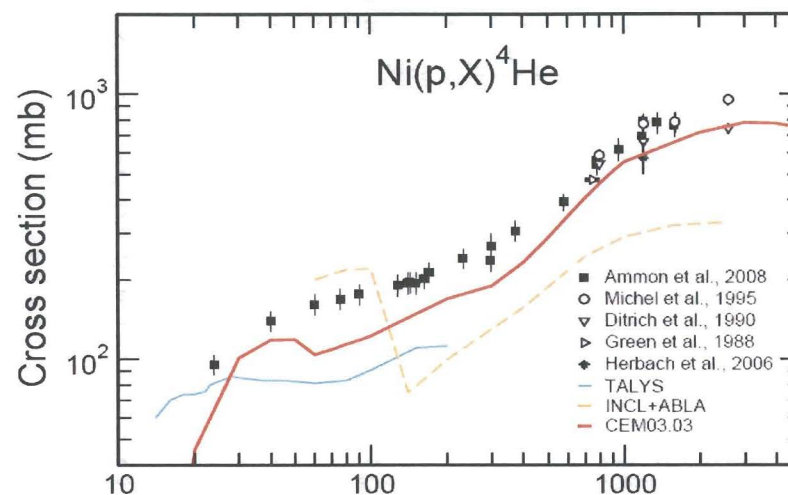
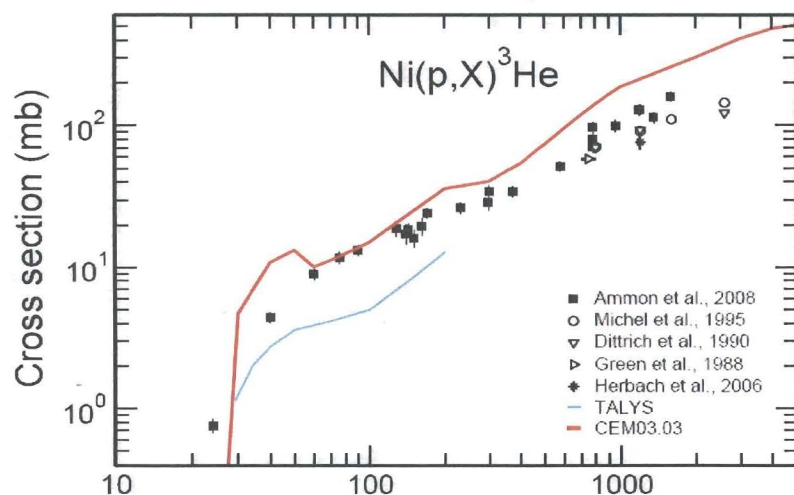


The Ammon et al. data and TALYS and INCL+ABLA results are from:

Nuclear Instruments and Methods in Physics Research B 266 (2008) 2–12

Cross sections for the production of helium, neon and argon isotopes
by proton-induced reactions on iron and nickel

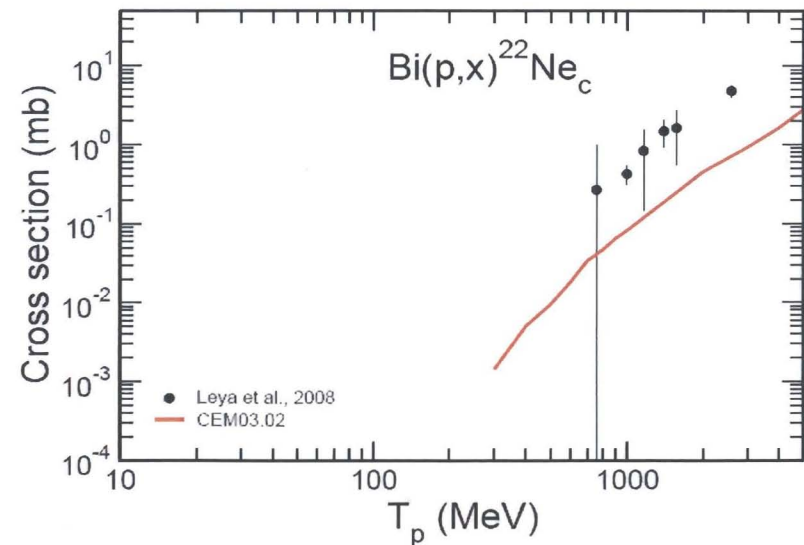
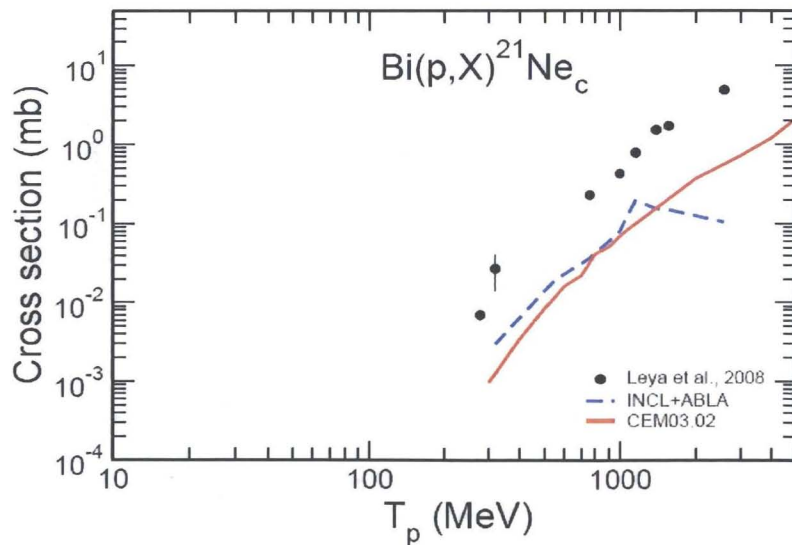
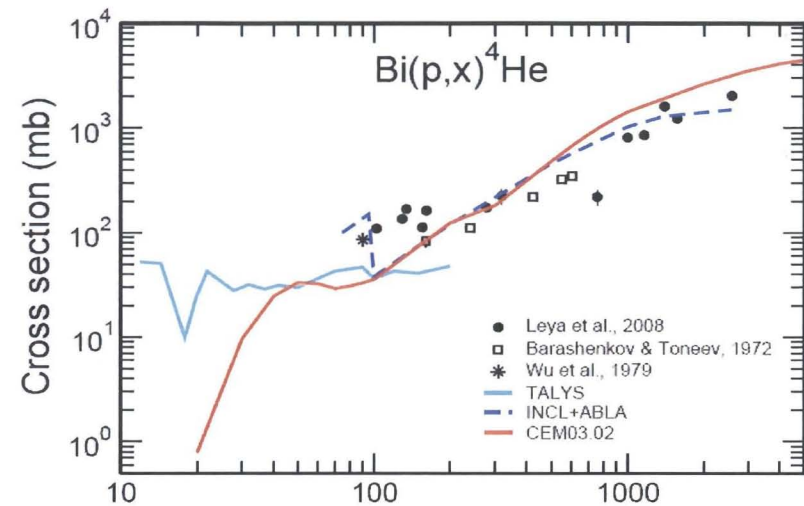
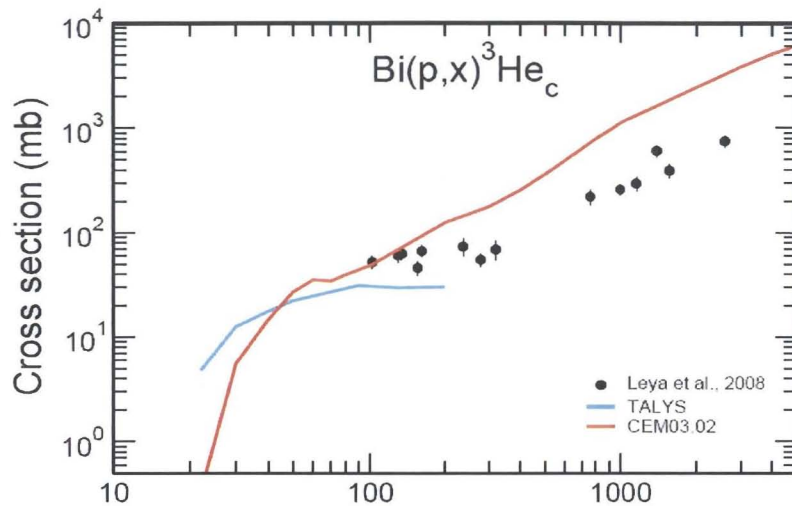
K. Ammon^{a,*}, I. Leya^a, B. Lavielle^b, E. Gilibert^b, J.-C. David^c, U. Herpers^d, R. Michel^c





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

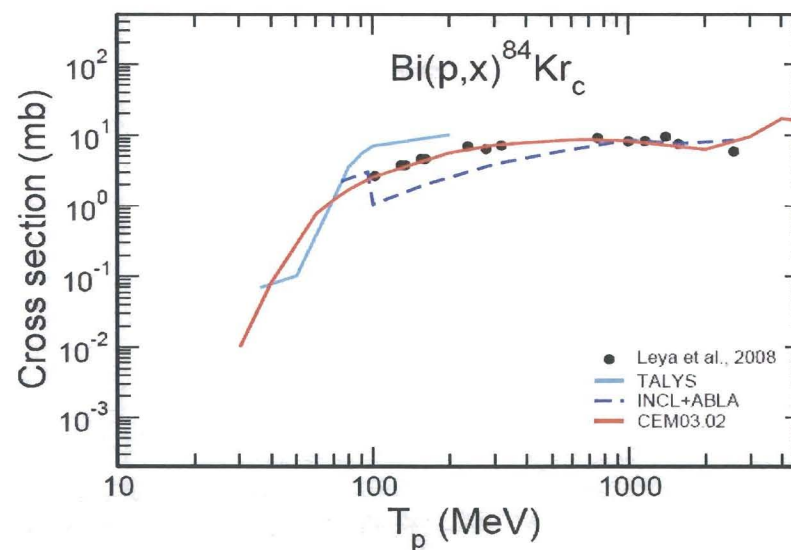
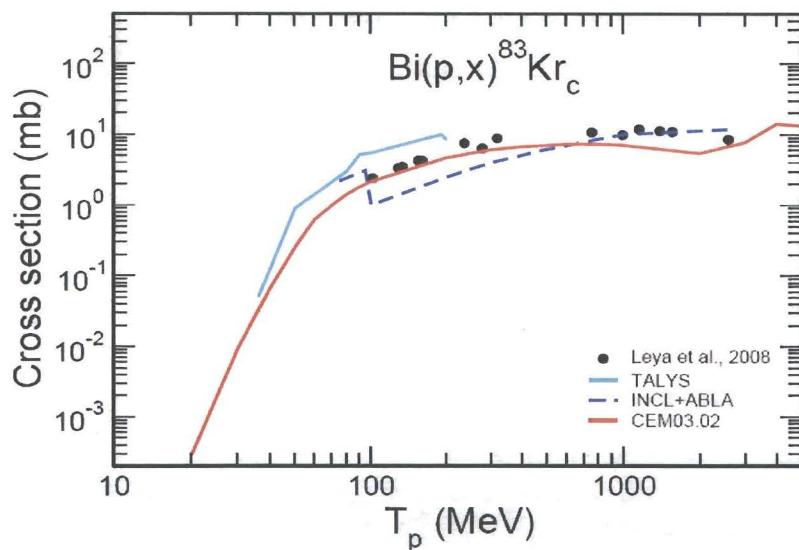
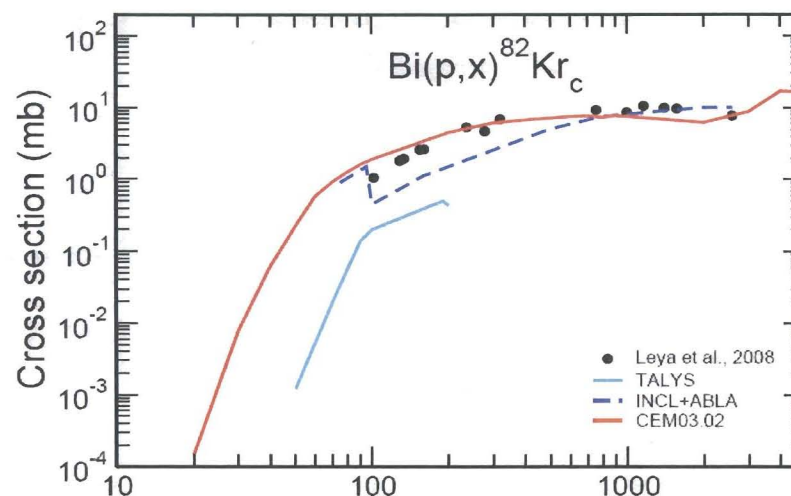
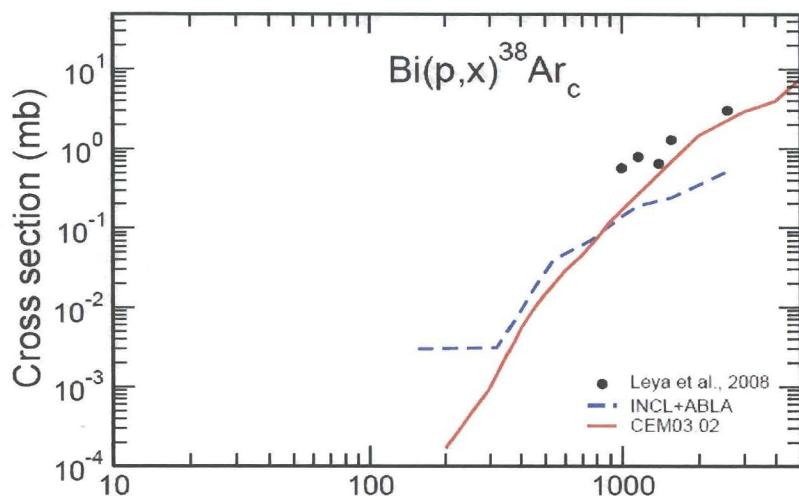
I. Leya, J.-C. David, S. Leray, R. Wieler, and R. Michel, "Production of noble gas isotopes by proton-induced reactions on bismuth," NIM B 266 (2008) 1030-1042





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

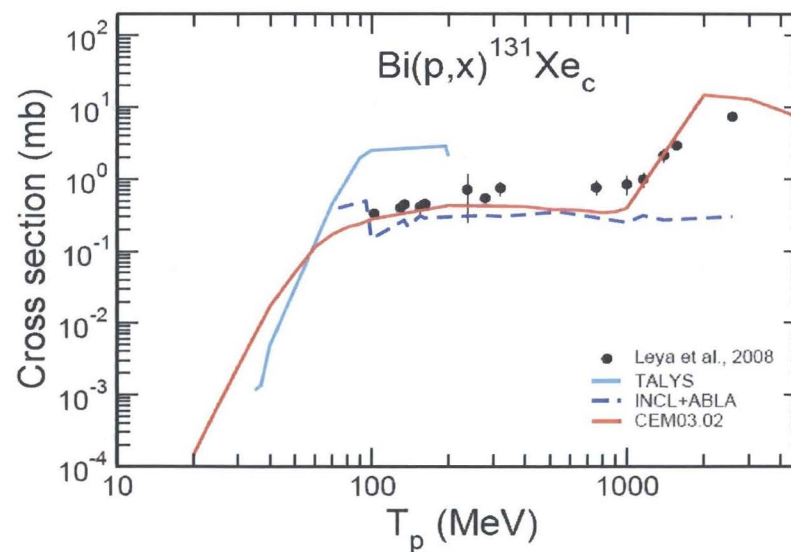
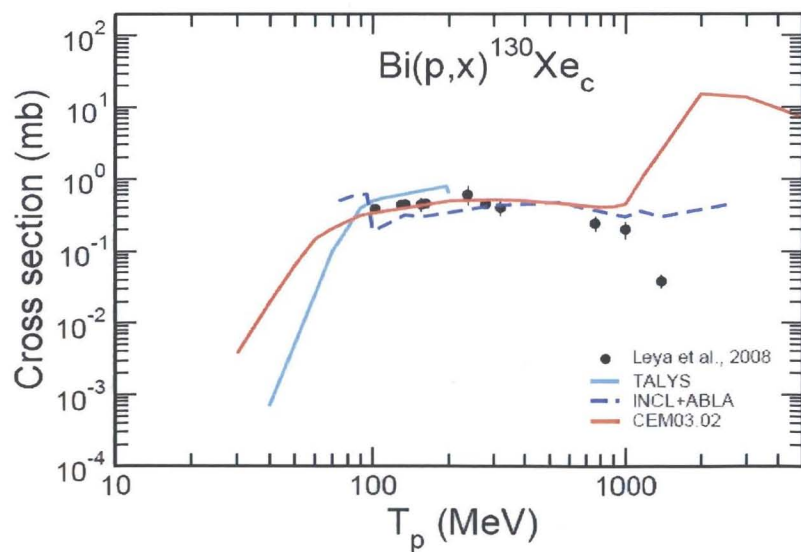
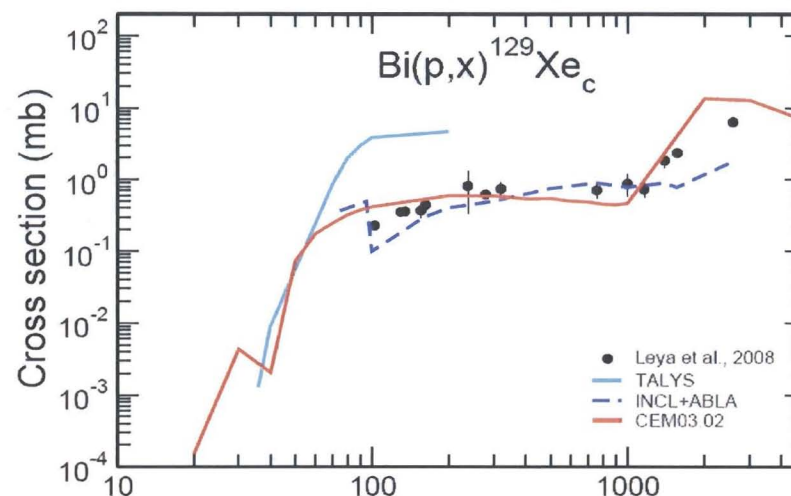
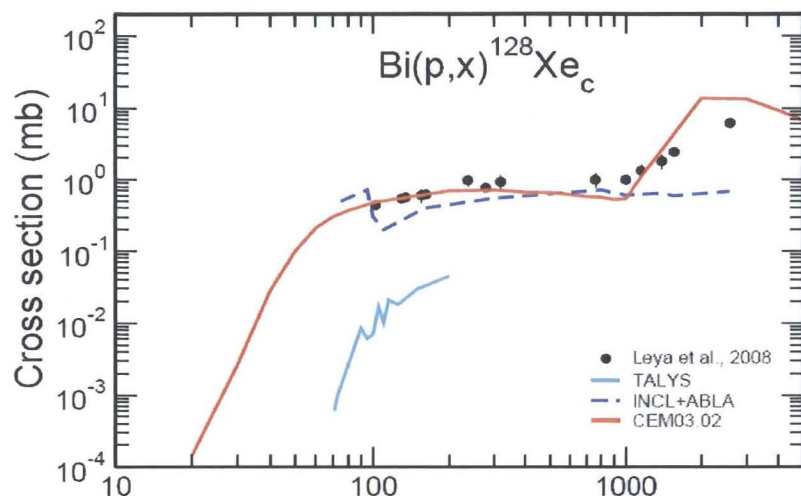
I. Leya, J.-C. David, S. Leray, R. Wieler, and R. Michel, "Production of noble gas isotopes by proton-induced reactions on bismuth," NIM B 266 (2008) 1030-1042





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

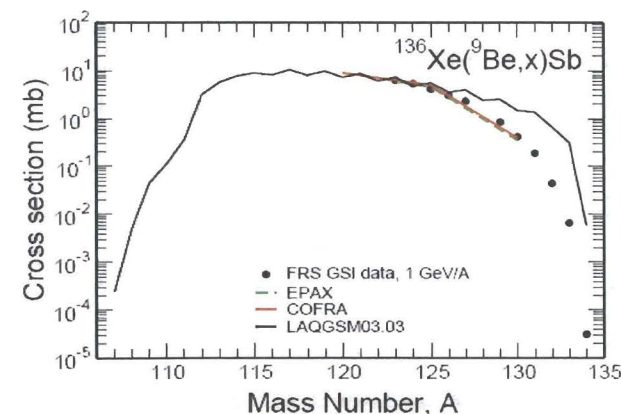
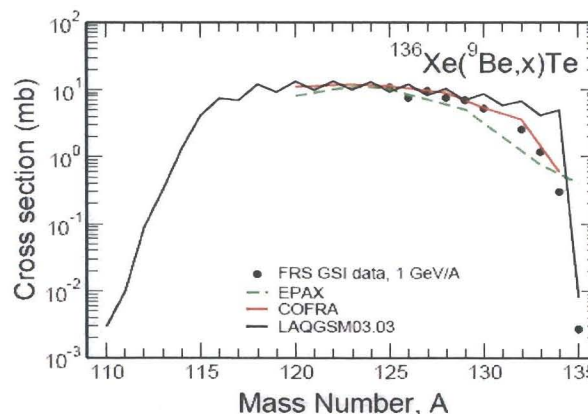
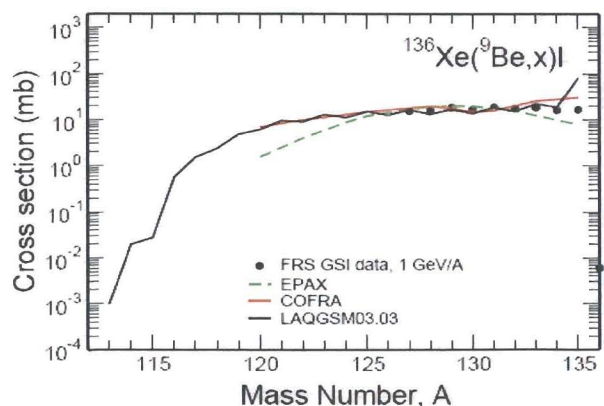
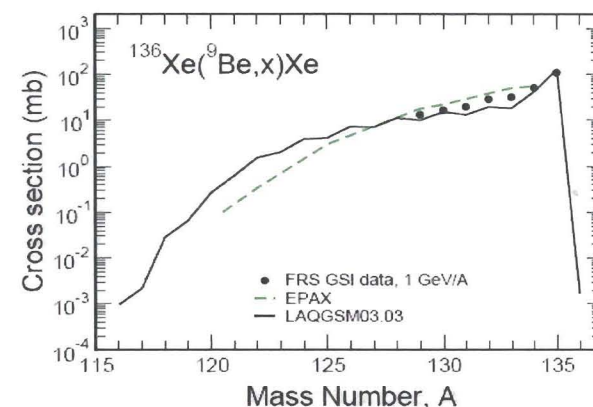
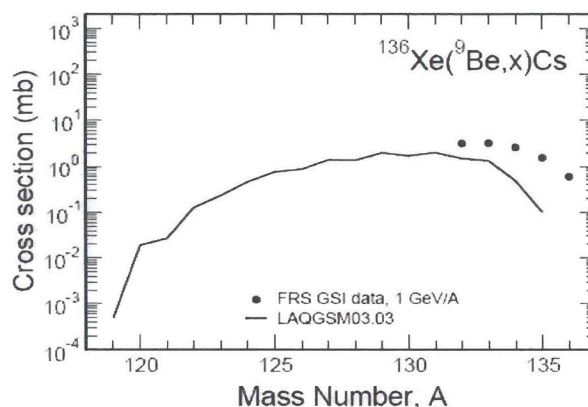
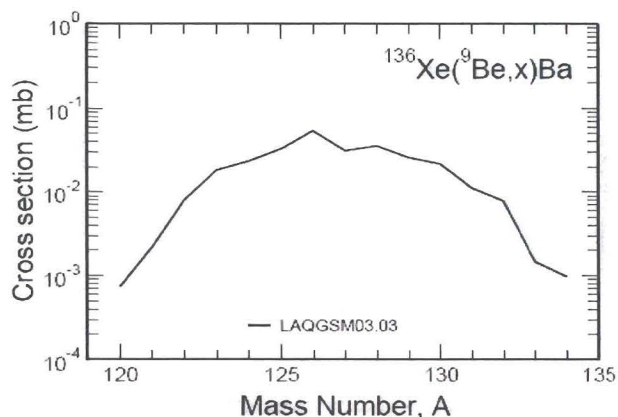
I. Leya, J.-C. David, S. Leray, R. Wieler, and R. Michel, "Production of noble gas isotopes by proton-induced reactions on bismuth," NIM B 266 (2008) 1030-1042





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

J. Benlliure, et al., "Production of medium-mass neutron-rich nuclei in reactions induced by ^{136}Xe projectiles at 1 A GeV on a beryllium target," arXiv: 0807.2851 [nucl-ex] 17 Jul 2008.





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

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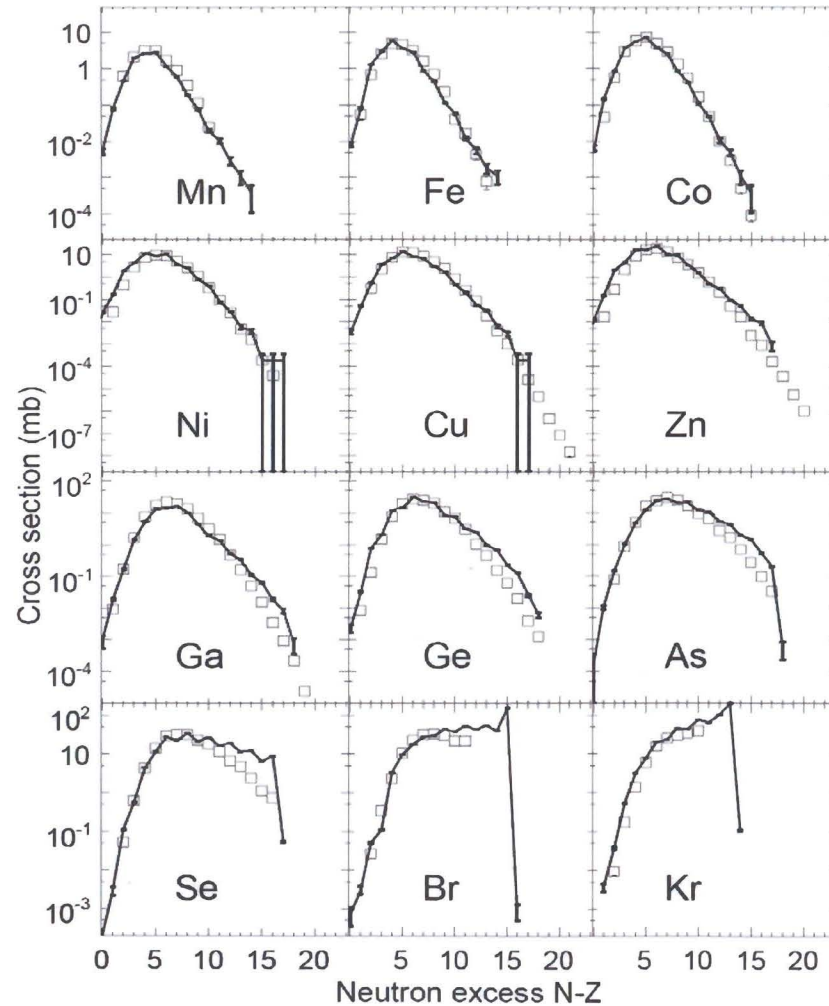


Figure 9: Experimental data for $^{86}\text{Kr}+^9\text{Be}$ reactions compared to LAQGSM model.

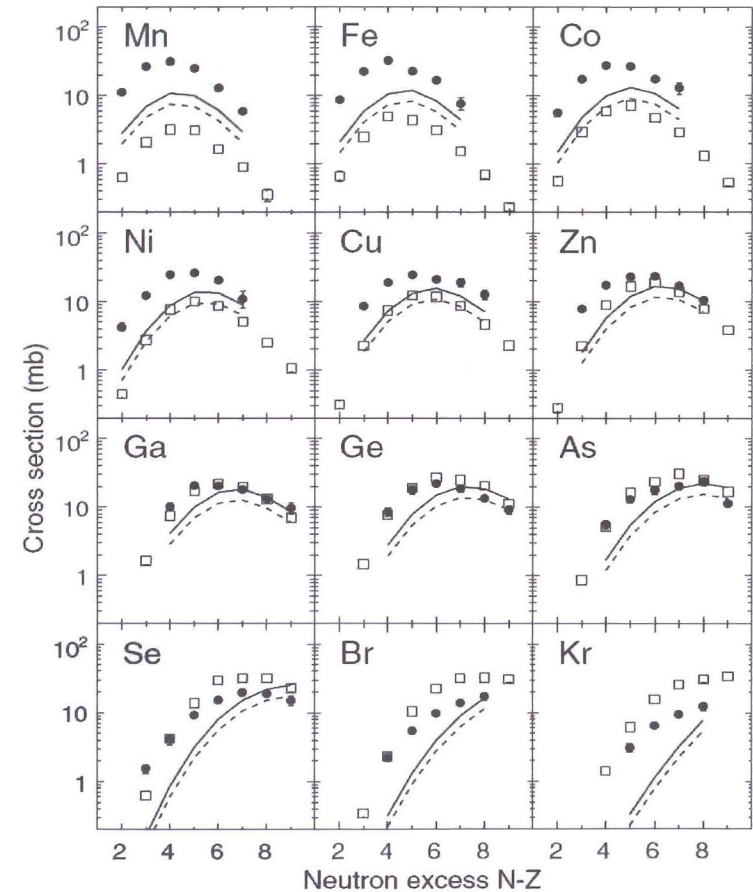
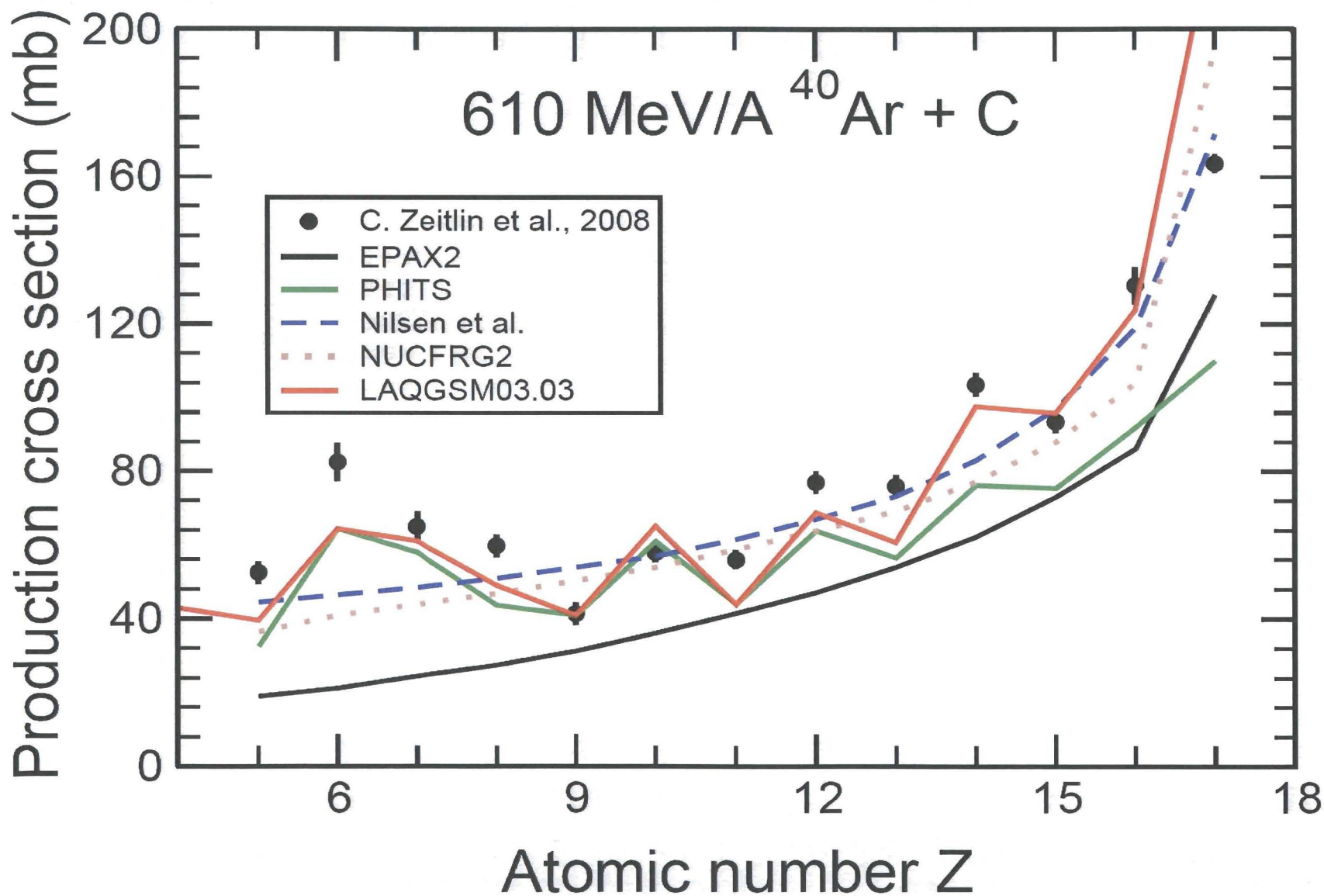


FIG. 8. Measured cross sections presented as isotope distributions for $25 \leq Z \leq 36$ elements detected in the $^{86}\text{Kr}+^{181}\text{Ta}$ reactions (filled circles) and in the $^{86}\text{Kr}+^9\text{Be}$ reactions (open squares) at 64 MeV/nucleon. EPAX calculations are shown as dashed ($^{86}\text{Kr}+^9\text{Be}$) and solid ($^{86}\text{Kr}+^{181}\text{Ta}$) curves.



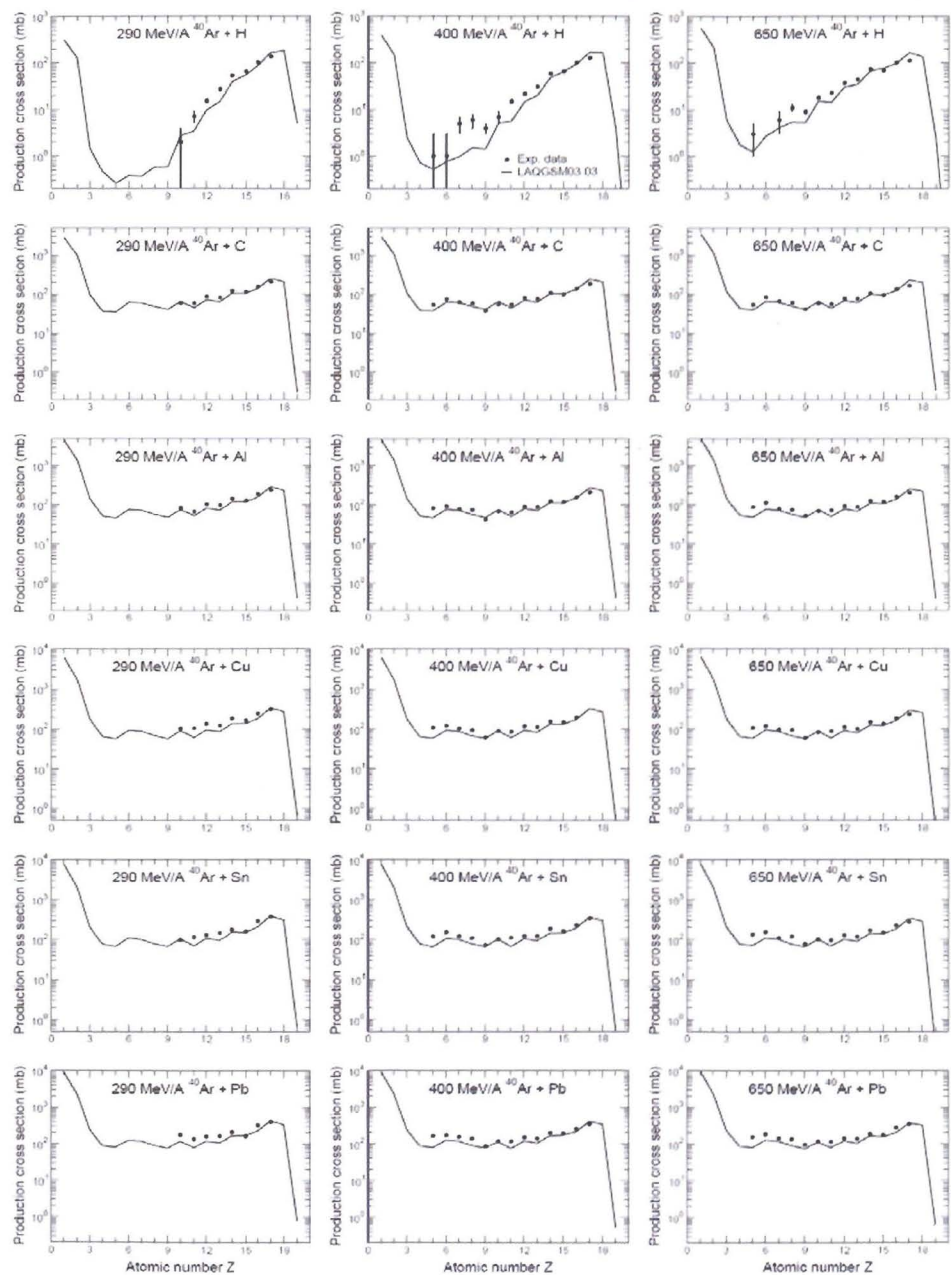
Zeitlin et al. data and EPAX2, PHITS, Nilsen et al., and NUCFRG2 results are from:
C. Zeitlin et al., Phys. Rev. C 77 (2008) 034605

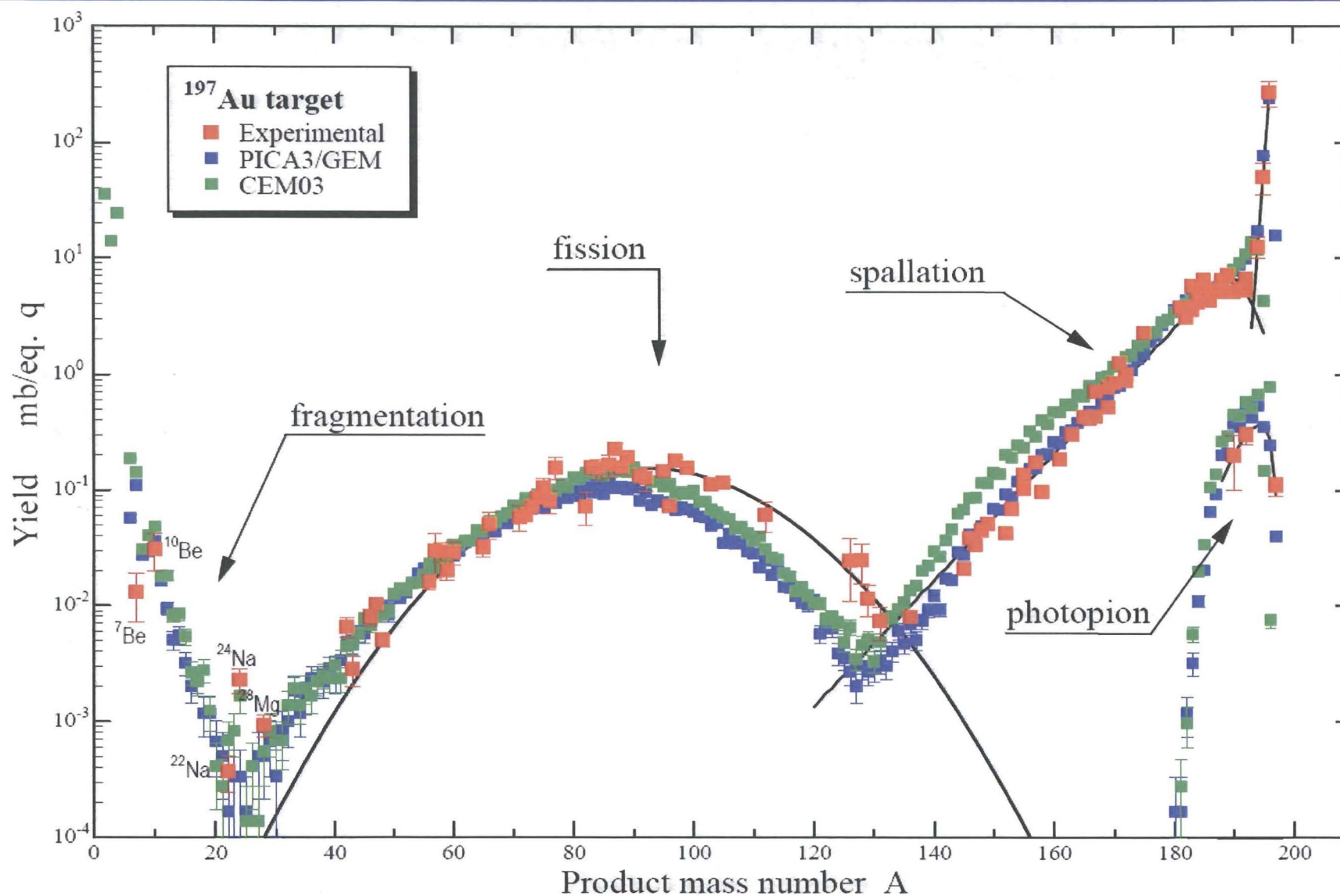


Invited Seminar, Nuclear Theory Group, IPHC, Strasbourg, France, October 21, 2008, S. G. Mashnik, LA-UR-08-xxxx



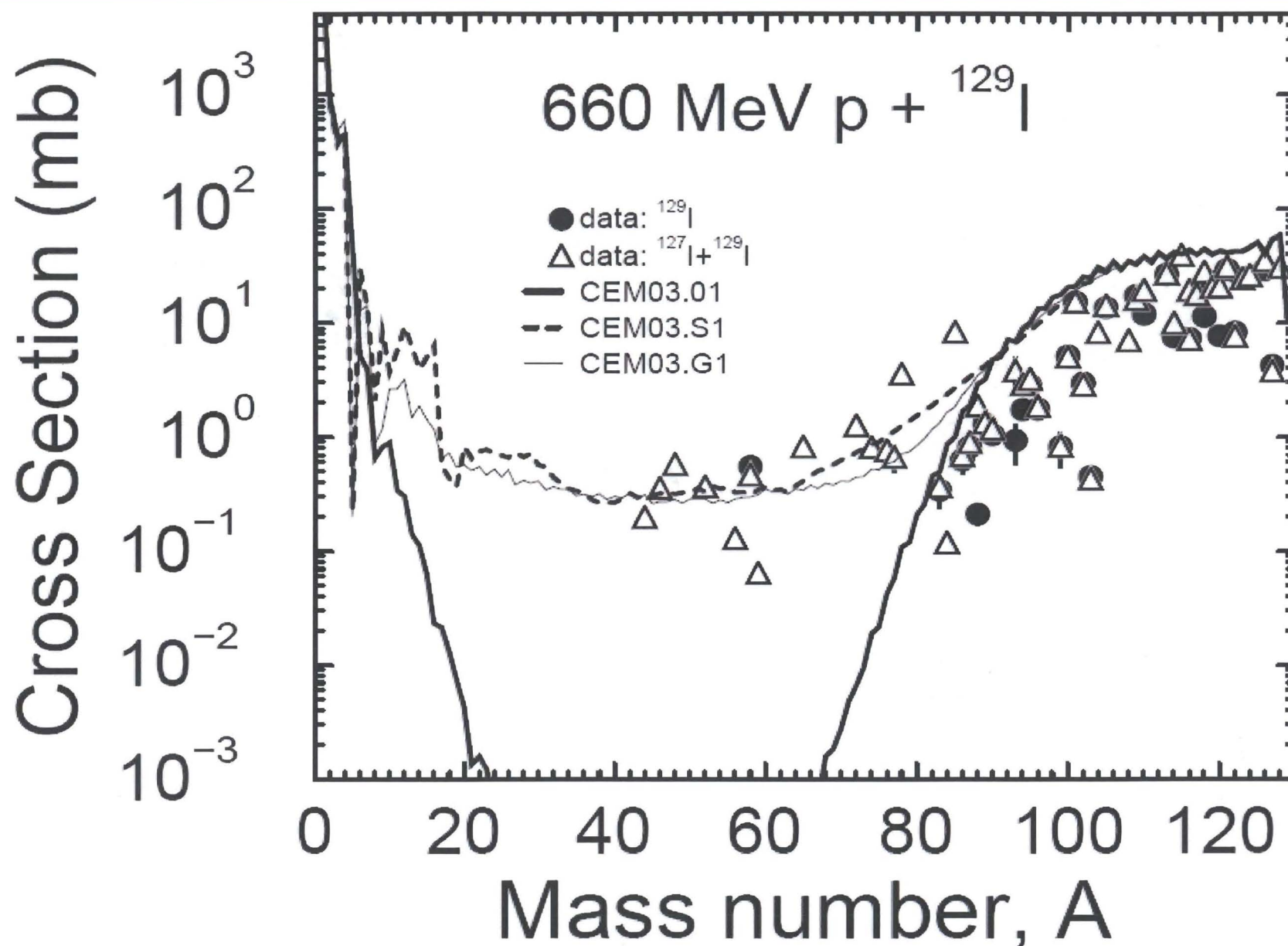
Zeitlin et al. data are from: C. Zeitlin et al., Phys. Rev. C 77 (2008) 034605



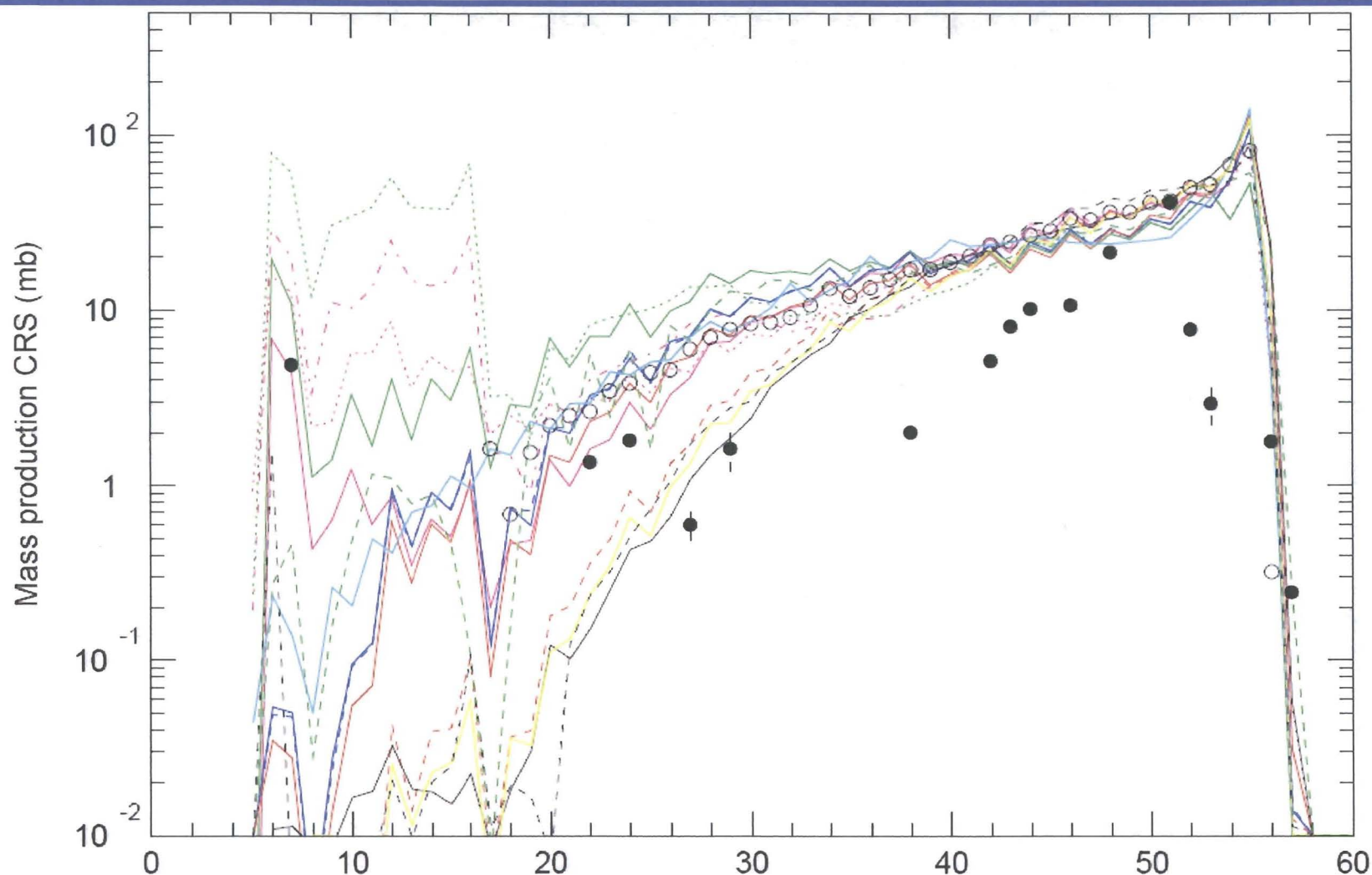


$E_0 = 1$ GeV bremsstrahlung induced data:

Koh Sakamoto, J. Nucl. Radiochem. Sci. 4 (2003) A9



JINR data: J. Adam et al., Part. Nucl. Lett. 4 (2004) 53 (arXiv:nucl-ex/0403056)



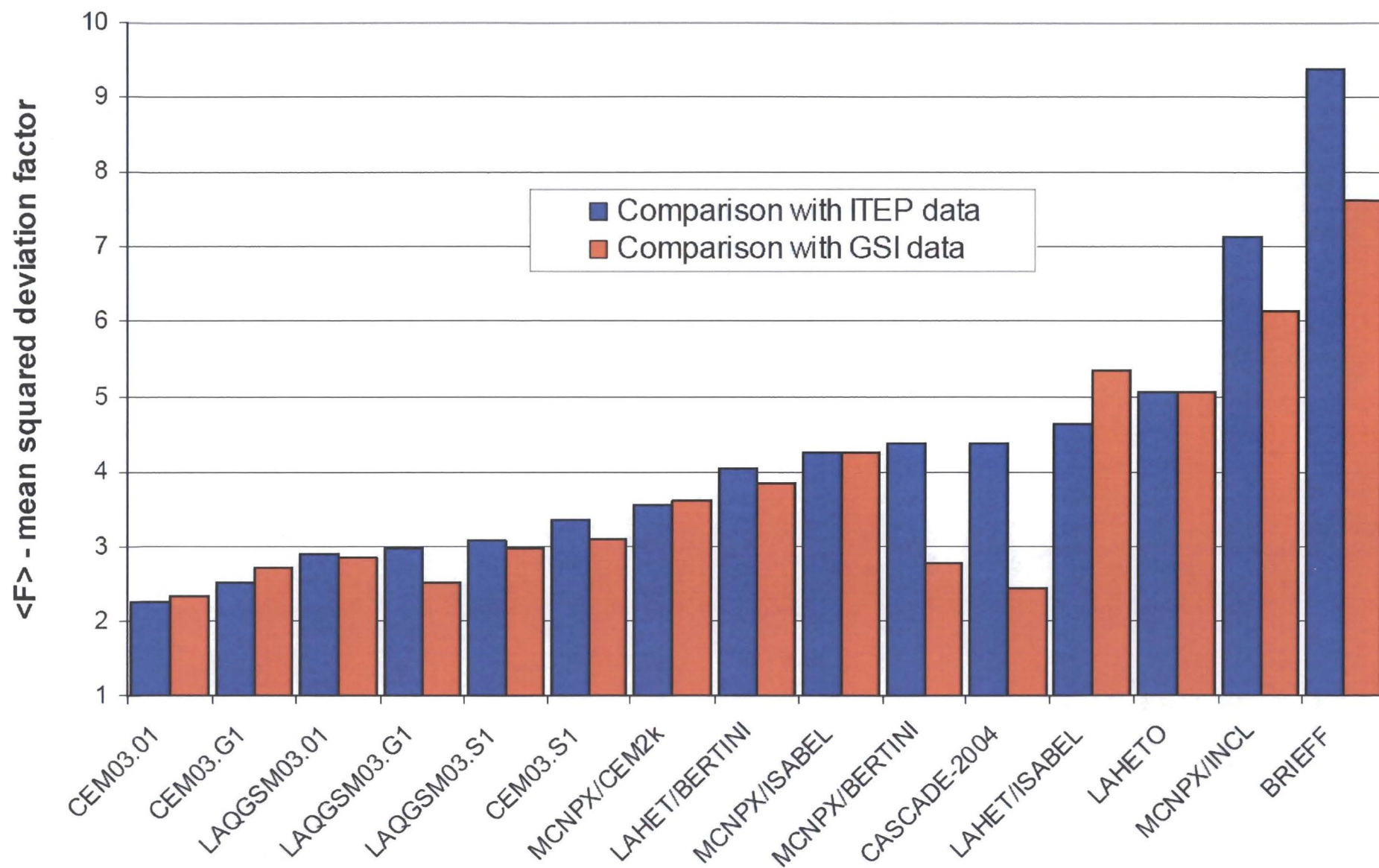
Experimental and calculated 1.5 GeV p + ^{56}Fe product yields as functions of A:

GIS data (open circles) : C. Villagrasa-Canton et al., Phys. Rev. C75 (2007) 044603.

ITEP data (filled circles): ISTC Project # 3266, Yu. E. Titarenko et al., LANL Reports LA-UR-06-4098 and LA-UR-07-2659; Proc. ND2007, E-print: arXiv:0705.1020.



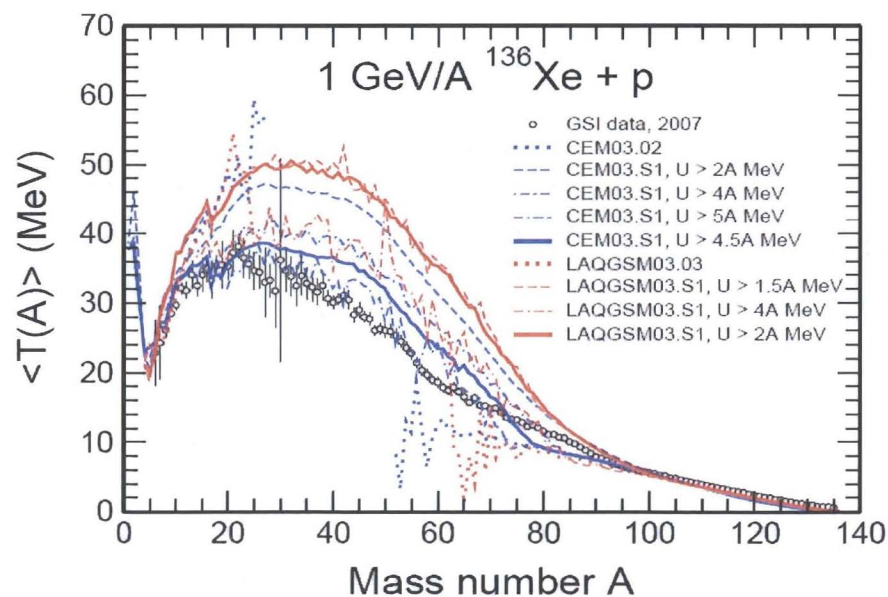
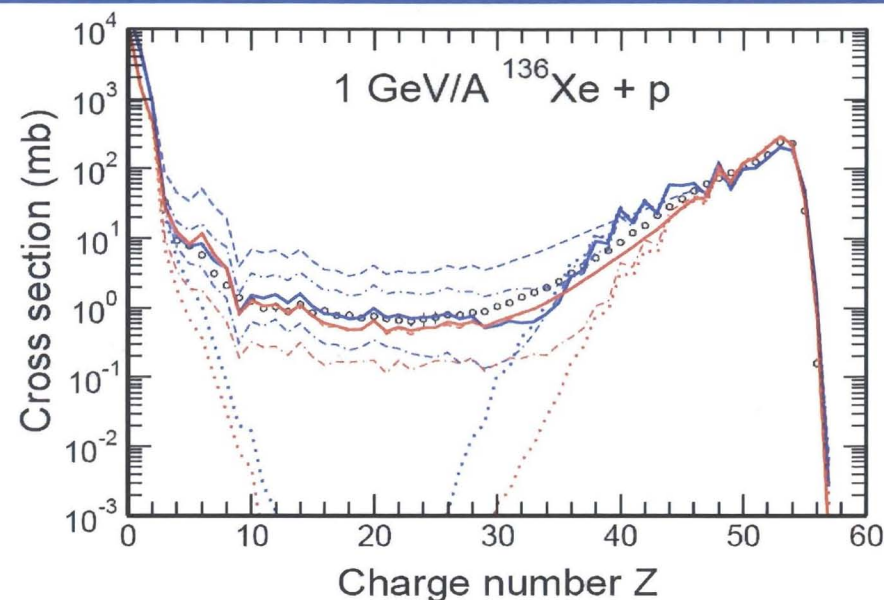
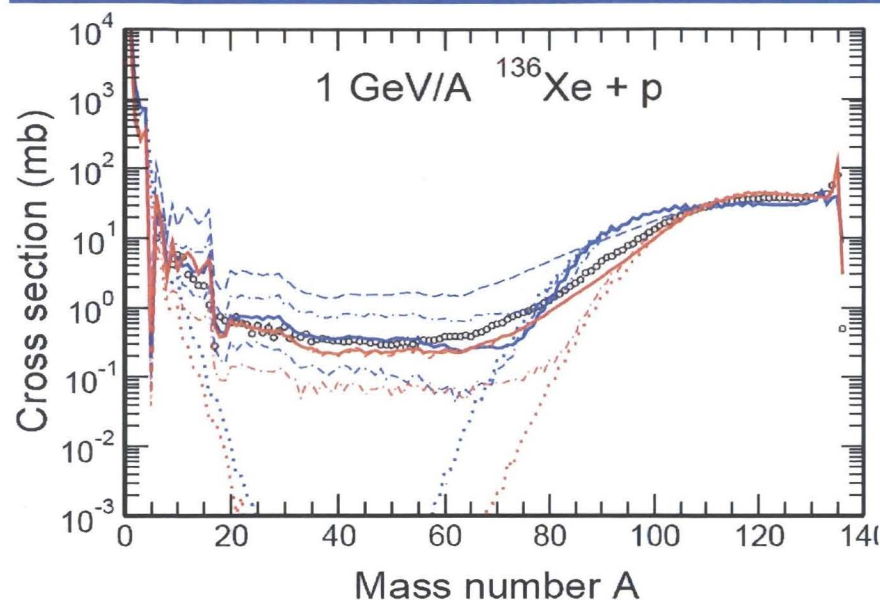
Theoretical predictions on $^{56}\text{Fe}(p,x)$ residuals



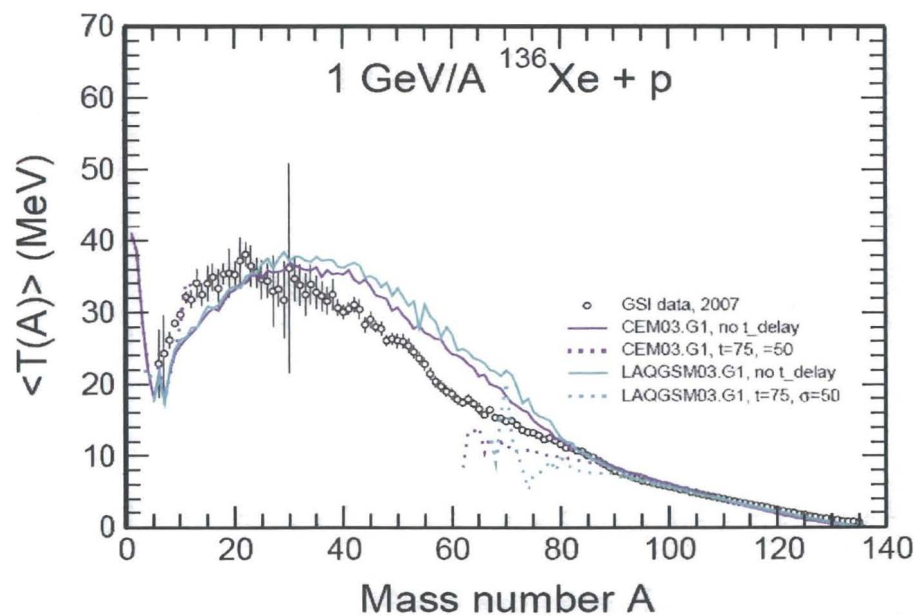
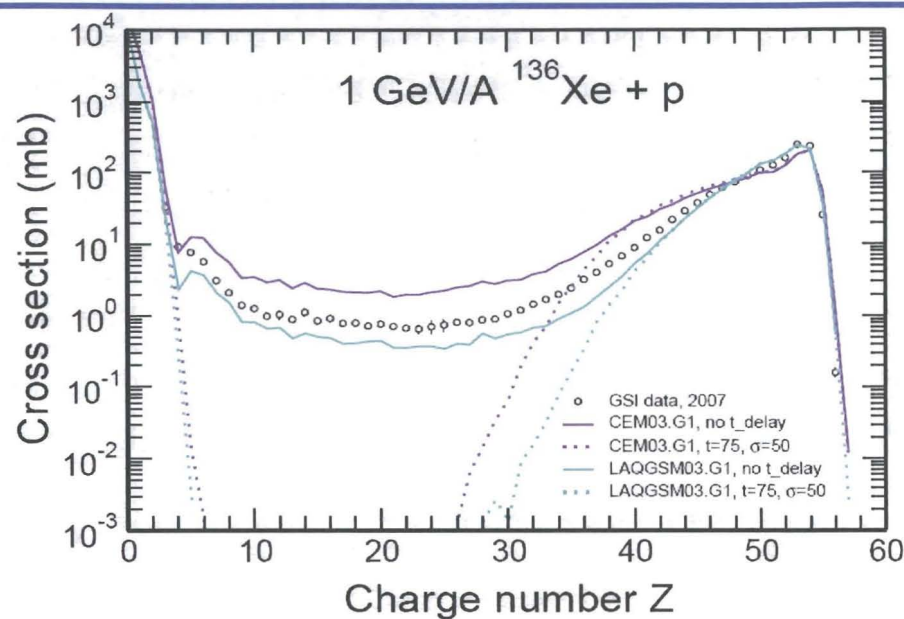
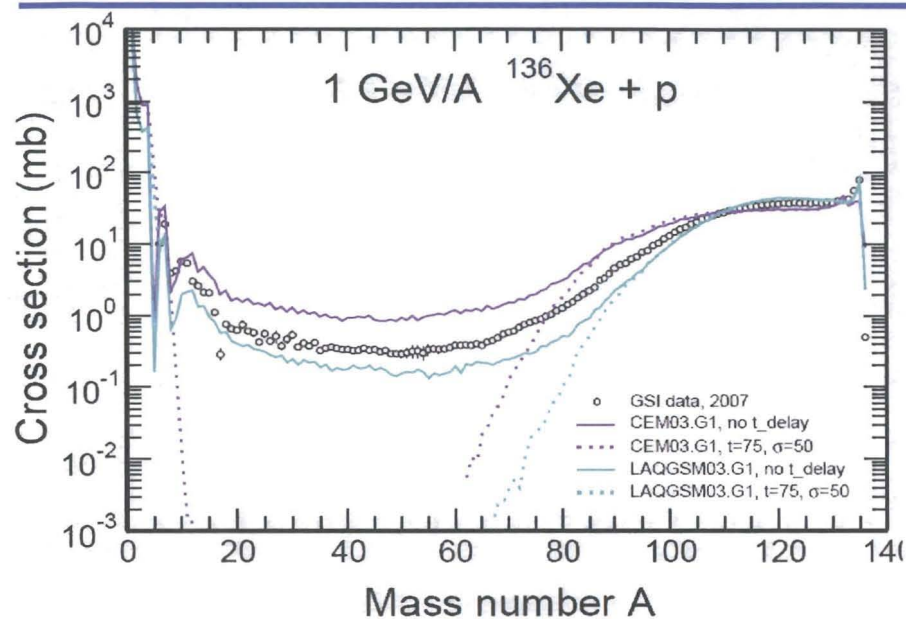


CEM03.S1 and LAQGSM03.S1 are exactly the same as CEM03.01 and LAQGSM03.01, but consider also multifragmentation of excited nuclei produced after the preequilibrium stage of reactions, when their Excitation energy is above $2A$ MeV, using the Statistical Multifragmentation Model (SMM) by Botvina et al.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

- J. P. Bondorf, A. S. Botvina, A. S. Iljinov, I. N. Mishustin, and K. Snepken, Phys. Rep. 257 (1995) 13;
- A. S. Botvina, A. S. Iljinov, I. N. Mishustin, J. P. Bondorf, R. Donangelo, and K. Snappen, Nucl Phys. A475 (1987) 663;
- A. S. Botvina, K. K. Gudima, A. S. Iljinov, and I. N. Mishustin, Phys. At. Nucl. 57 (1994) 628;
- A. S. Botvina, A. S. Iljinov, and I. N. Mishustin, Nucl. Phys. A507 (1990) 649;
- A. S. Botvina, A. S. Iljinov, and I. N. Mishustin, Sov. J. Nucl. Phys. 42 (1985) 712;
- A. S. Botvina, present ICTP-IAEA Advanced Workshop on Model Codes, 2008.



GSI data (symbols): P. Napolitani *et al.*, Phys. Rev. C 76 (2007) 0646091



GSI data (symbols): P. Napolitani *et al.*, Phys. Rev. C 76 (2007) 0646091



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**).

- L. G. Sobotka, M. A. McMahan, R. J. McDonald, C. Signarbieux, G. J. Wozniak, M. L. Padgett, J. H. Gu, Z. H. Liu, Z. Q. Yao, and L. G. Moretto, Phys. Rev. Lett. 53 (1984) 200;
- R. J. Charity, M. A. McMahan, G. J. Wozniak, R. J. McDonald, L. G. Moretto, D. G. Sarantites, L. G. Sobotka, G. Guarino, A. Pantaleo, L. Fiore, A. Gobbi, and K. D. Hildenbrand, Nucl. Phys. A483 (1988) 371;
- R. J. Charity, D. R. Bowman, Z. H. Liu, R. J. McDonald, M. A. McMahan, G. L. Wozniak, L. G. Moretto, S. Bardley, W. L. Kenoe, and A. C. Mignerey, Nucl. Phys. A476 (1988) 516;
- R. J. Charity, Phys. Rev. C 58 (1988) 1073;
- R. J. Charity, L. G. Sobotka, J. Cibor, K. Hagel, M. Murray, J. B. Natowitz, R. Wada, Y. El Masri, D. Fabris, G. Nebbia, G. Viesti, M. Cinausero, E. Fioretto, G. Prete, A. Wagner, and H. Xu, Phys. Rev. C 63 (2001) 024611; <http://www.chemistry.wustl.edu/~rc/gemini/>;
- R. J. Charity, present ICTP-IAEA Advanced Workshop on Model Codes, 2008.



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

- Pencil beam of U-238 – zero radius
- MCNPX run $1.e+09$ 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 RSICC 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 RSICC 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!