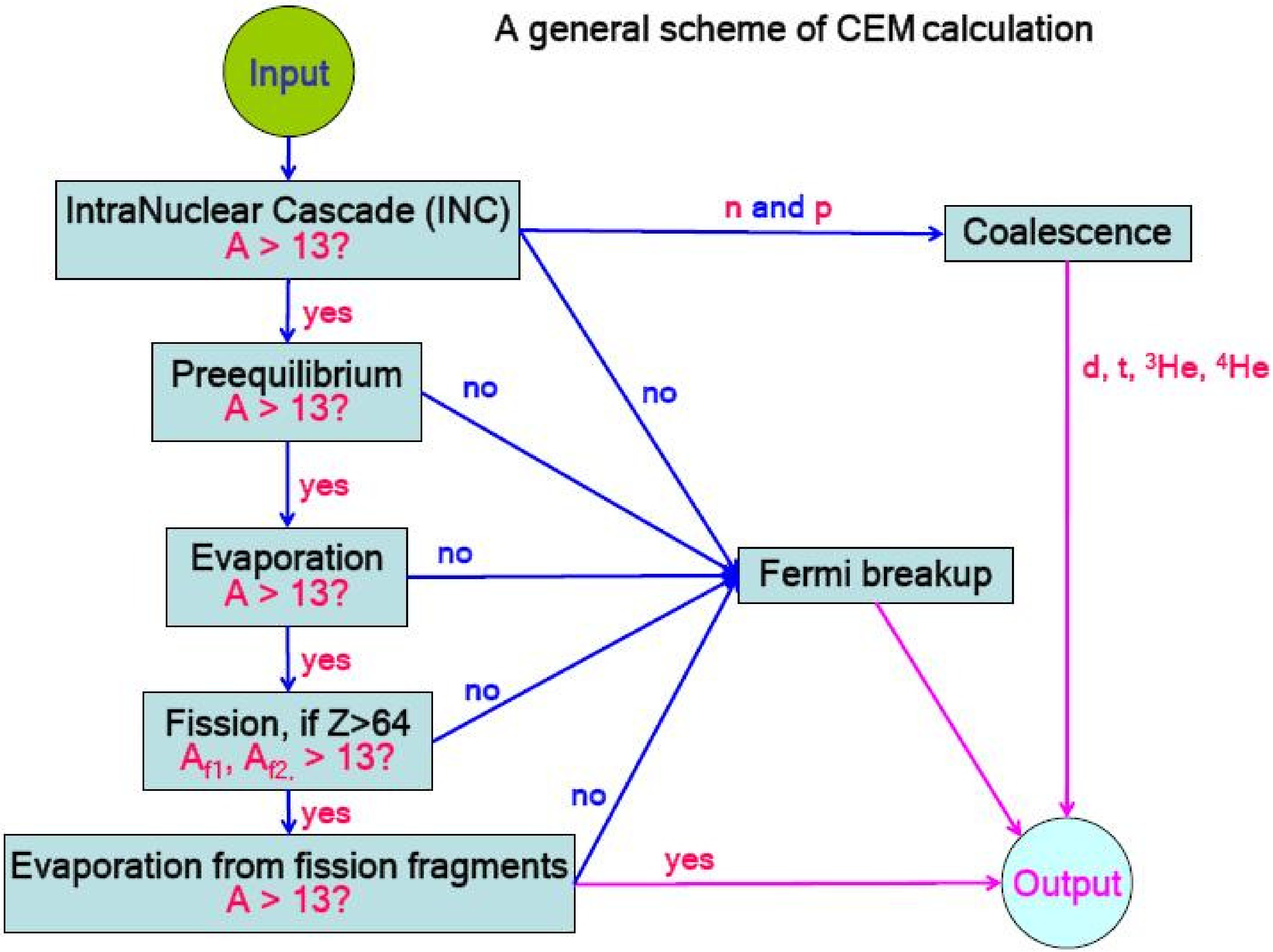
Benchmarking the CEM03.03 event generator

K. K. Gudima[1], M. I. Baznat[1]
S. G. Mashnik[2], and A. J. Sierk[2]
[1]Institute of Applied Physics, Academy of Science of Moldova,
Chişinău, Moldova
[2]Los Alamos National Laboratory, Los Alamos, NM 87545, USA

Benchmarking the CEM03.03 event generator

- Introduction
- INC of CEM03.03
- The coalescence model
- Preequilibrium [the Modified Exciton Model (MEM)]
- Evaporation /Fission
- Fermi break-up of light nuclei (A<13)
- Benchmarking results
- Summary

Benchmarking the CEM03.03 event generator



Gudima, 4-8 May 2009, Vienna

Benchmarking the CEM03.03 event generator

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 Polinica 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).

Benchmarking the CEM03.03 event generator

Cascade-exciton model (CEM) considers the nuclear reaction as proceeding through three stages - cascade, pre-equilibrium and equilibrium (or compound nucleus) - unlike the two-stage Serber mechanism . So, in a general case three components will contribute to each experimentally measured value.

$$\sigma(\boldsymbol{p})\mathrm{d}\boldsymbol{p} = \sigma_{\mathrm{in}}\left[N^{\mathrm{cas}}(\boldsymbol{p}) + N^{\mathrm{prq}}(\boldsymbol{p}) + N^{\mathrm{eq}}(\boldsymbol{p})\right]\mathrm{d}\boldsymbol{p}.$$

$$N^{\mathrm{cas}}(\boldsymbol{p})\mathrm{d}\boldsymbol{p} = \frac{1}{\sigma_{\mathrm{in}}}\int_0^R \mathrm{d}^2 b \int_{r>R} \mathrm{d}\boldsymbol{r} \int_0^{t_{\mathrm{cas}}} \mathrm{d}t\, f_b^{\mathrm{cas}}(\boldsymbol{r},\boldsymbol{p},t)\mathrm{d}\boldsymbol{p},$$

$$N^{\mathrm{p.eq.}}(\boldsymbol{p})\mathrm{d}\boldsymbol{p} = \int_{t_{\mathrm{cas}}}^{t_{\mathrm{eq}}} \sum_n \lambda_c^j(n,E,T)P(E,n,t)\frac{\partial(p,\Omega)}{\partial(T,\Omega)}F(\Omega)\mathrm{d}T\mathrm{d}\Omega.$$

$$N^{\mathrm{eq}}(\boldsymbol{p})\mathrm{d}\boldsymbol{p} = \int_{t_{\mathrm{eq}}}^{\infty} \mathrm{d}t \sum_n \lambda_c^j(n,E,T)P(E,n,t)\frac{\partial(p,\Omega)}{\partial(T,\Omega)}F(\Omega)\mathrm{d}T\mathrm{d}\Omega,$$

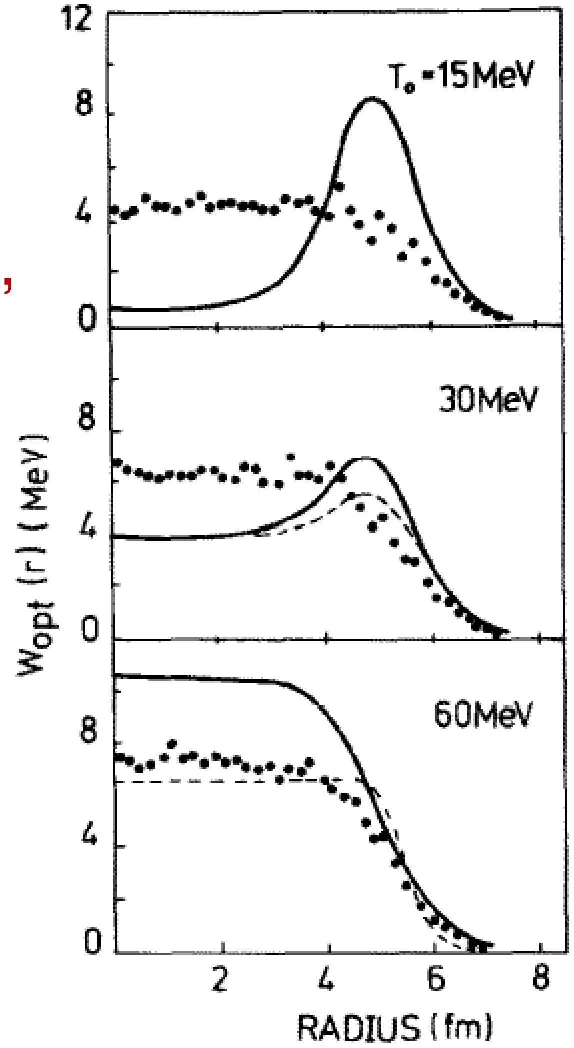
Benchmarking the CEM03.03 event generator

$$\mathscr{P} = |(W_{opt}^{cas}(r) - W_{opt}^{exp}(r))/W_{opt}^{exp}(r)|$$

$$W_{opt}(r) = -\tfrac{1}{2}\hbar\langle\sigma(v_{rel})v_{rel}\rangle.$$

$\mathscr{P}$ > 0.3 is condition to stop cascading, instead of cut-off energy condition $T<T_{cut}$=7-10 MeV

p + ^{56}Fe



Dots – cascade model calculation results
Lines are “experimental” data from
F. D. Becchetti Jr. and G. W. Greenlees, Phys. Rev. 182 (1969) 1190 (solid)
J. I. Menet, E. E. Gross, J. J. Malanify and A. Zucker, Phys. Rev. C4 (1974) 1114 (dashed)

Benchmarking the CEM03.03 event generator

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 Coalescence Model

- When the cascade stage of a reaction is completed, CEM03.03 use the coalescence model proposed for heavy ion collisions to “create” high-energy d, t, 3He, and 4He by final-state interactions among emitted cascade nucleons, already outside of the target nucleus. This means that the formation probability for, e.g. a deuteron is

$$W_d(\boldsymbol{p},\mathrm{b}) = \int\int d^3p_p\, d^3p_n\, \rho^C(p_p,\mathrm{b})\, \rho^C(p_n,\mathrm{b})\, \delta(p_p + p_n - p)\, \Theta(p_C - |p_p - p_n|),$$

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

$$\rho^C(p_p,b) = \int d^3r\, f^C(r,p,b)$$

and values of coalescence parameters

p_C = 150 , 175, 175, 175 MeV/c for d, t, He^3 and He^4.

Preequilibrium Reactions

At the preequilibrium stage of a reaction we take into account all possible nuclear transitions changing the number of excitons n

with $\Delta n = +2, -2,$ and 0, as well as possible multiple subsequent emissions of *n, p, d, t*, ^{3}He, and ^{4}He. The corresponding system of master equations describing the behavior of a nucleus at the preequilibrium stage is solved by the Monte-Carlo technique [K.K.G., S.G. Mashnik, V.D. Toneev, NP A401(1983)].

Evaporation/Fission

CEM03.03 use an extension of the Generalized Evaporation Model (GEM) code GEM2 by Furihata [Nucl. Instr. Meth. B 171 (2000)] after the preequilibrium stage of reactions to describe evaporation of nucleons, complex particles, and light fragments heavier than ^{4}He (up to ^{28}Mg) from excited compound nuclei and to describe their fission, if the compound nuclei are heavy enough to fission (($Z \geq 65$). The GEM2 includes up to 66 types of particles and fragments that can be evaporated from an excited nucleus.

- The Fermi Breakup Model

If the residual nuclei have atomic numbers with $A < 13$ CEM03.03 use the Fermi breakup model to calculate their further disintegration instead of using the preequilibrium and evaporation models. The newer versions of our codes use the Fermi breakup model also during the preequilibrium and/or evaporation stages of reactions, when the residual nucleus has an atomic number $A < 13$. The CEM03.03 code use the Fermi breakup model also to disintegrate the unstable fission fragments with $A < 13$ that can be produced in very rare cases of very asymmetric fission.

Benchmarking the CEM03.03 event generator

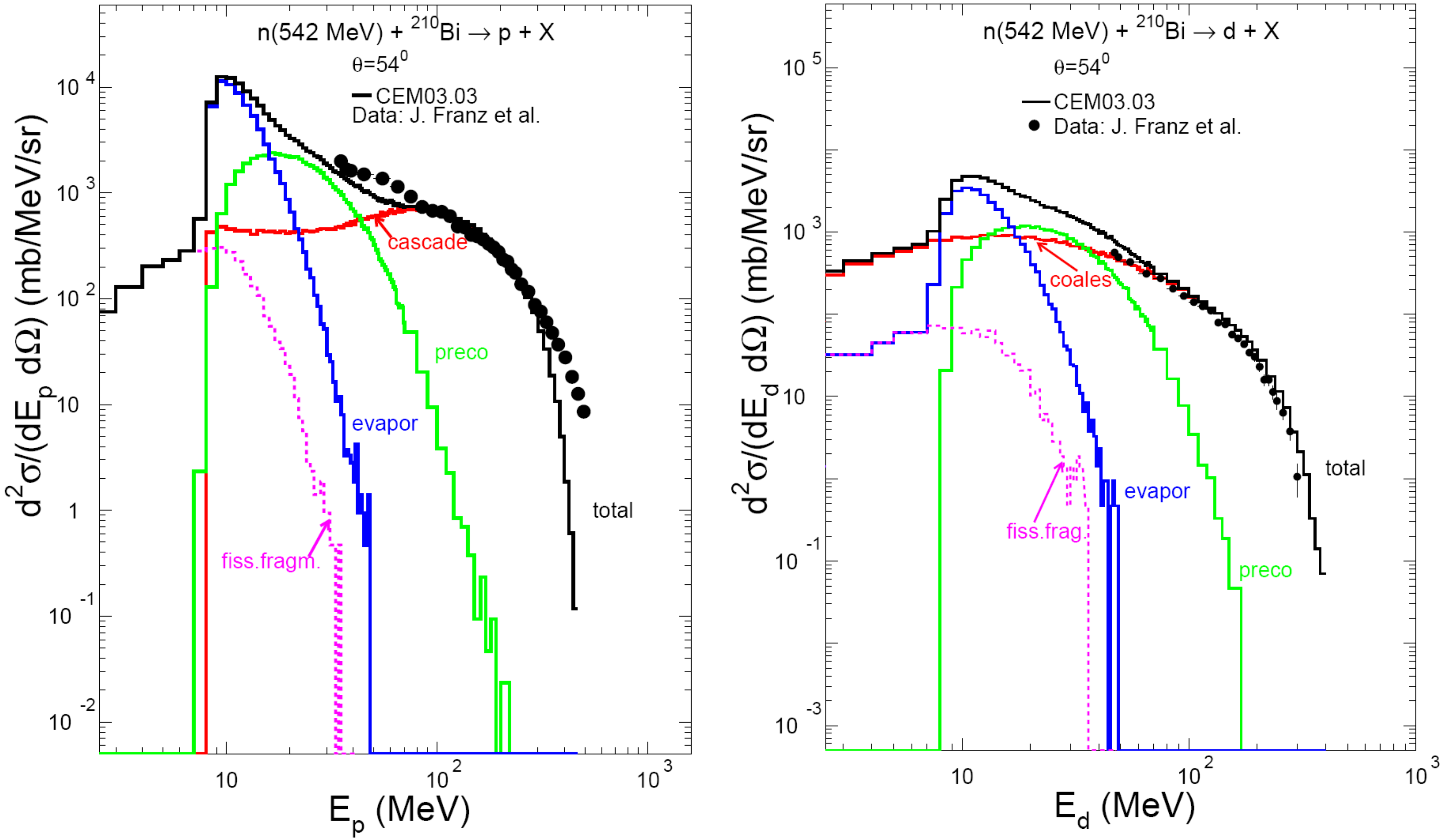
- Results

The results of benchmarking of CEM03.03 for particles production in different nuclear reactions and comparison with the experimental data are presented on the next figures

.

Generally spiking there is a good description of the data. There are some problems for small angles.

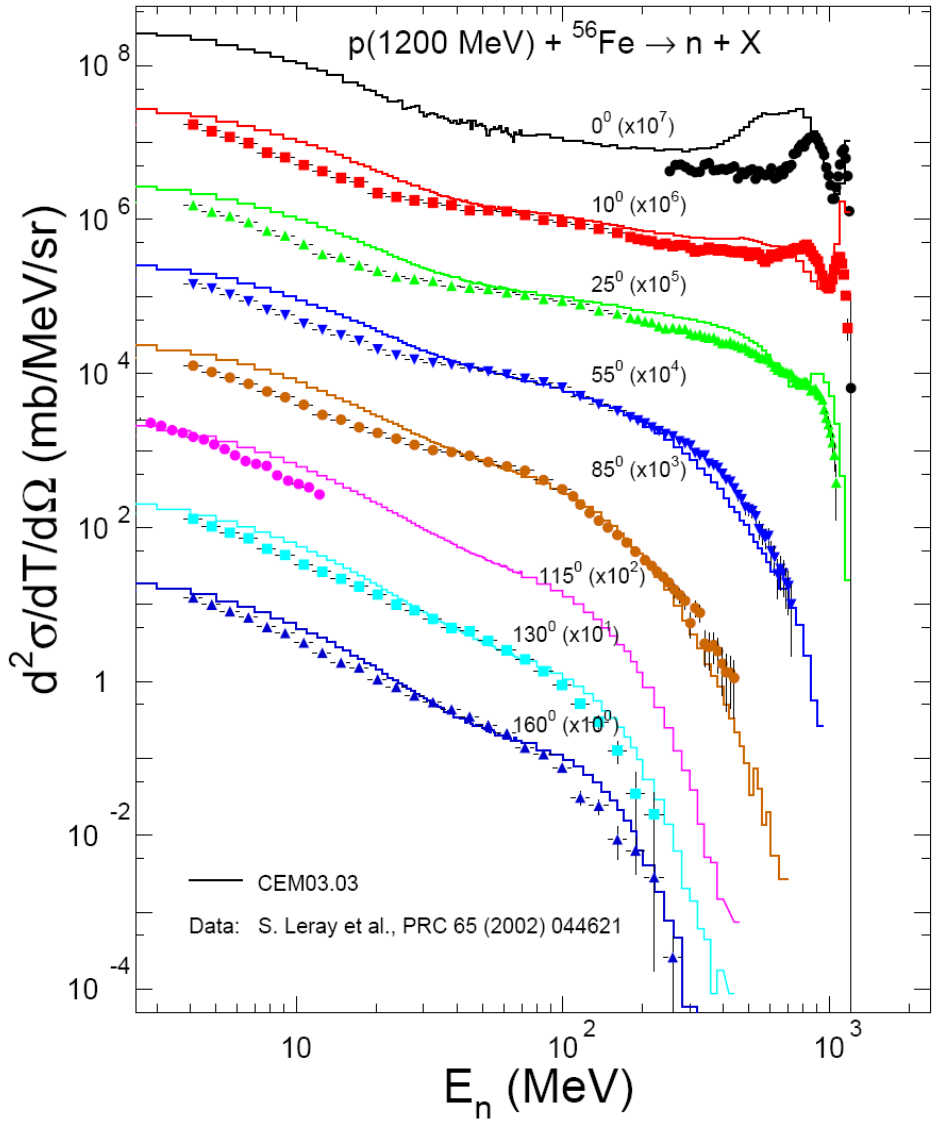
Benchmarking the CEM03.03 event generator

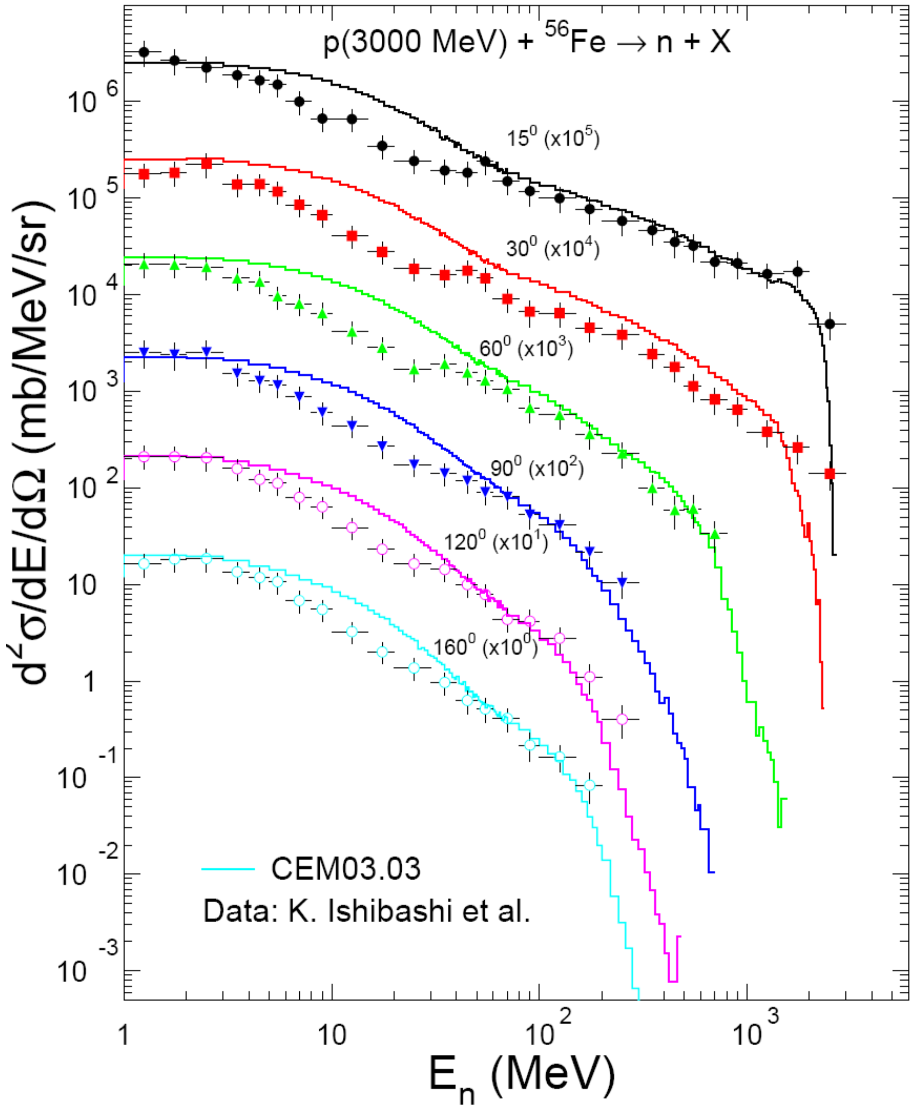


Gudima, 4-8 May 2009, Vienna

Benchmarking the CEM03.03 event generator

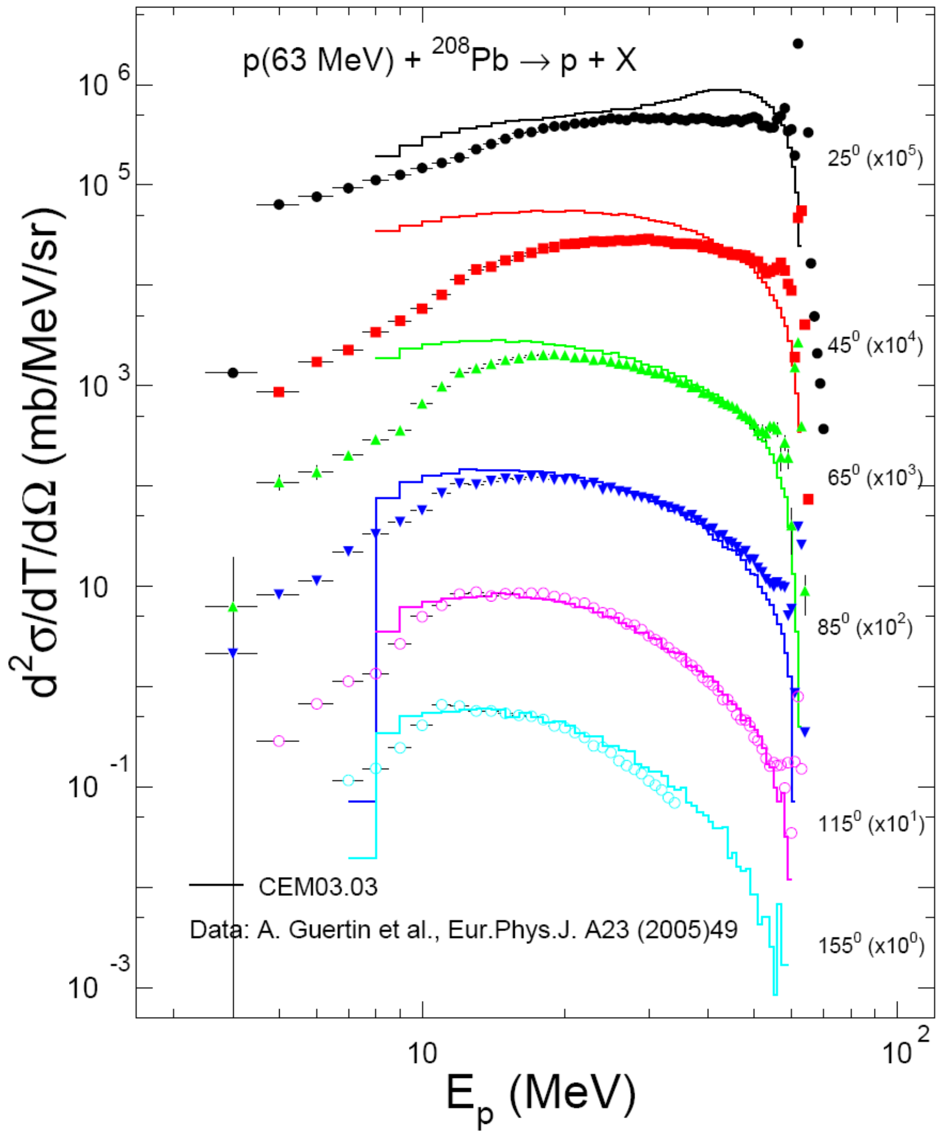
Neutron Spectra

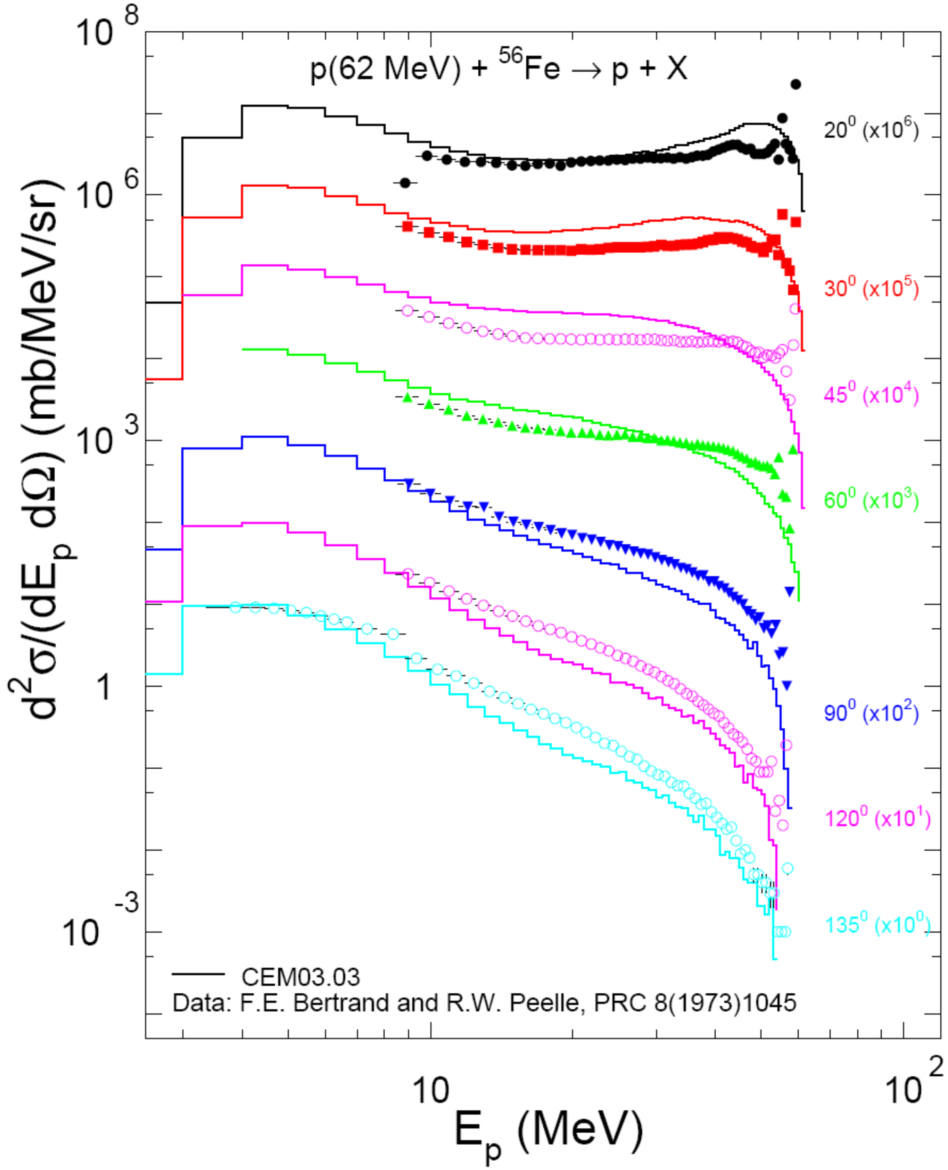




Benchmarking the CEM03.03 event generator

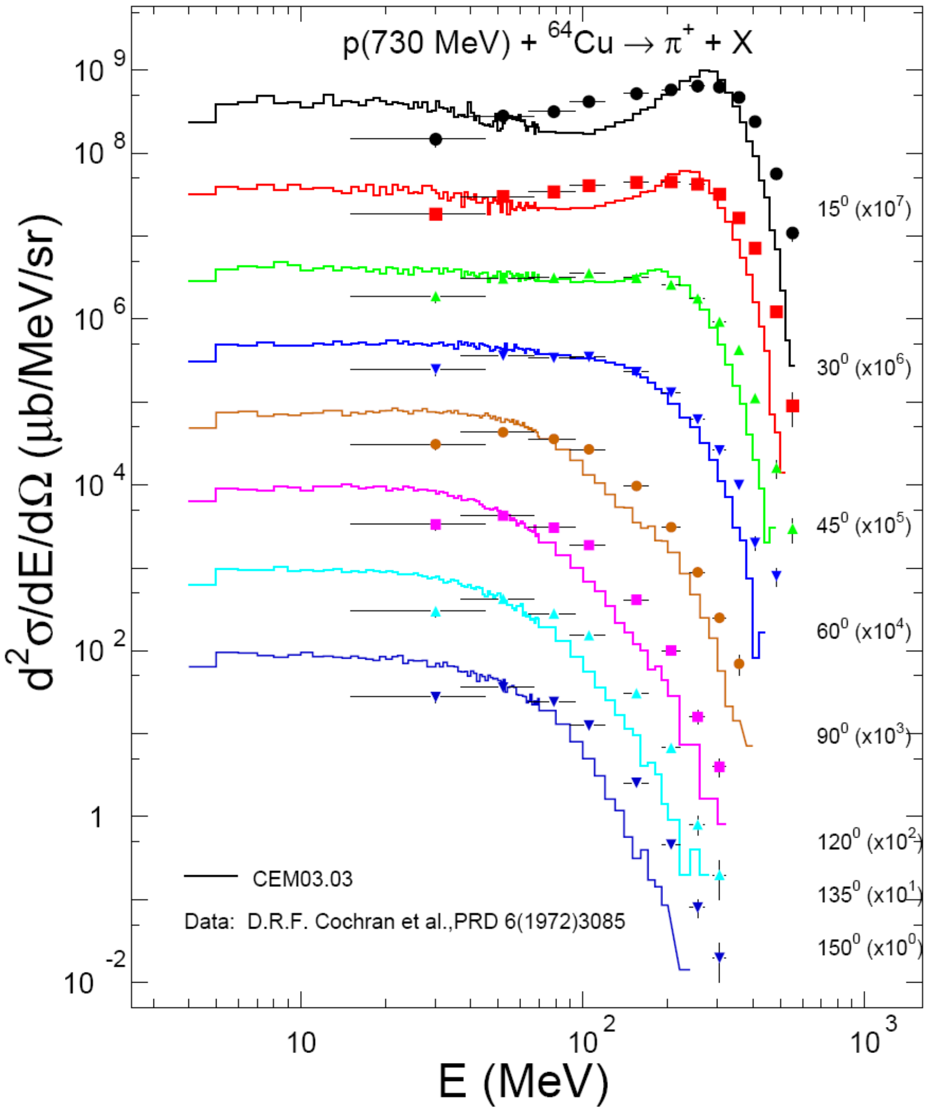
Proton Spectra

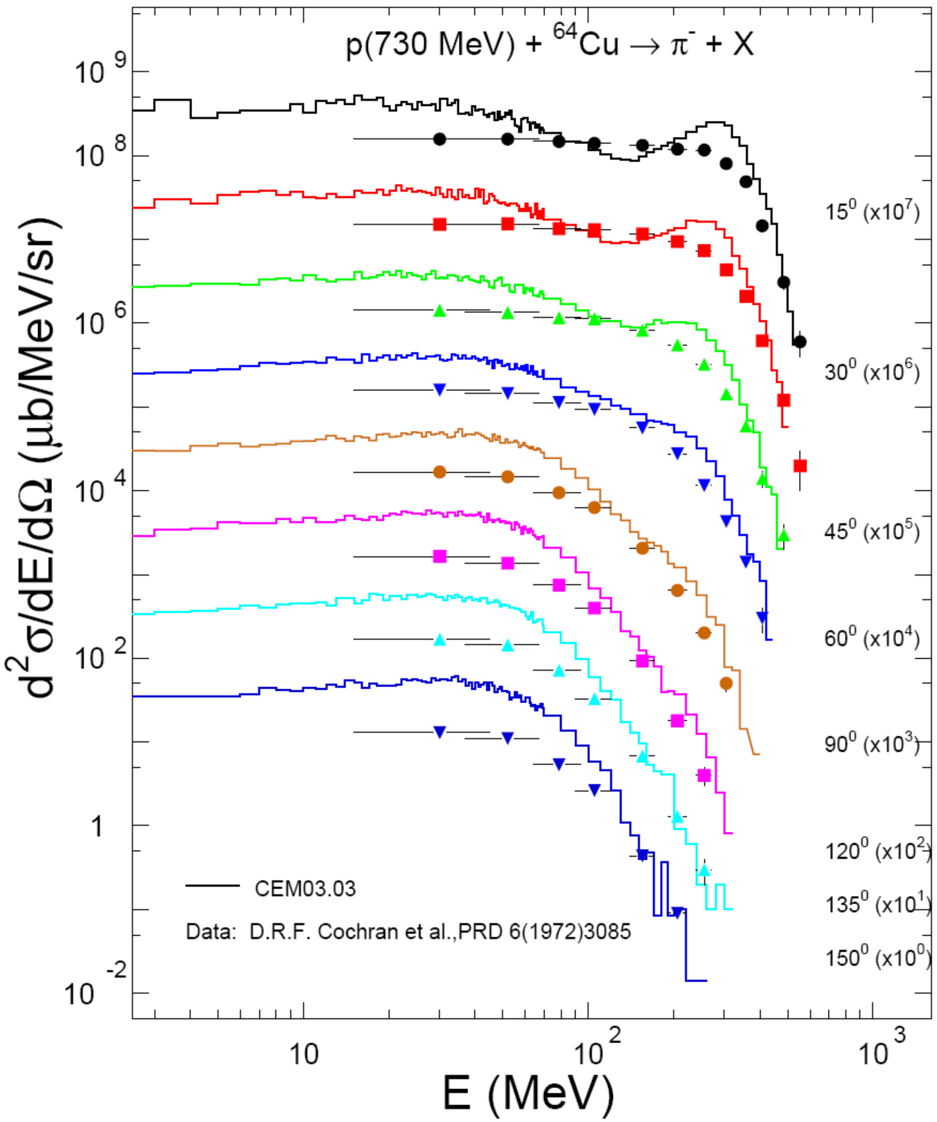




Benchmarking the CEM03.03 event generator

Pion Spectra

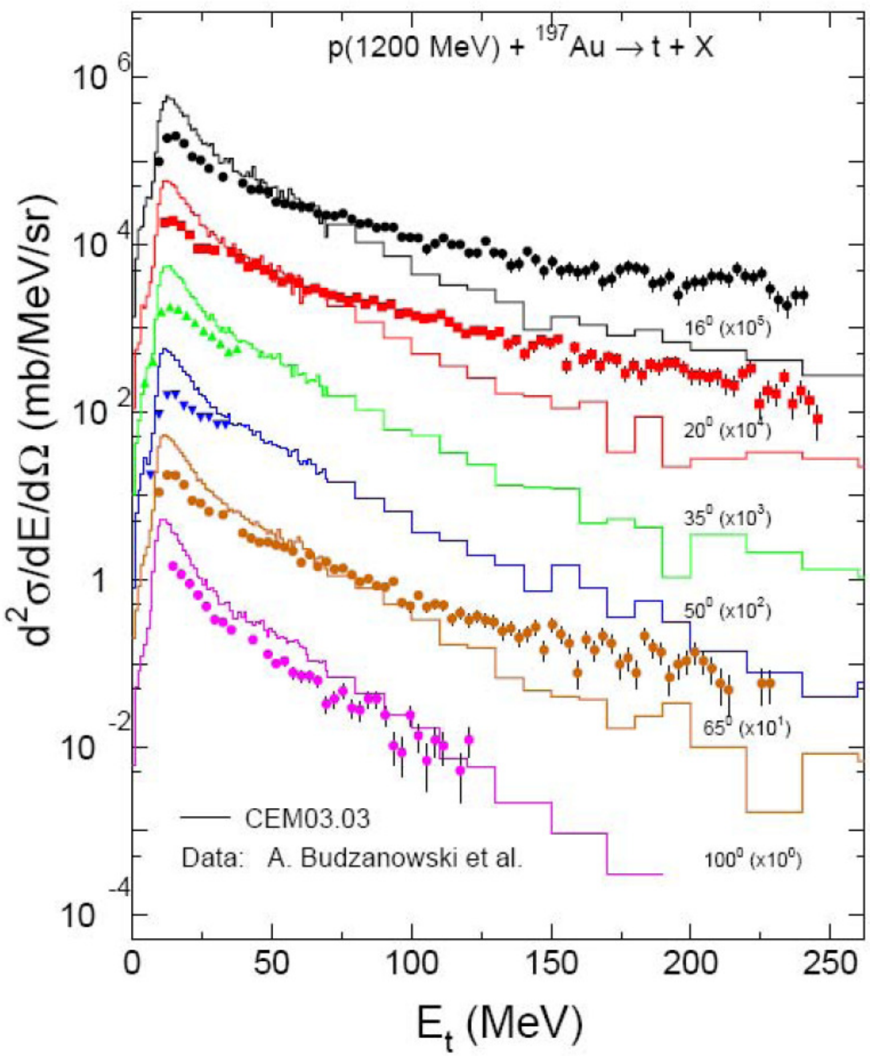


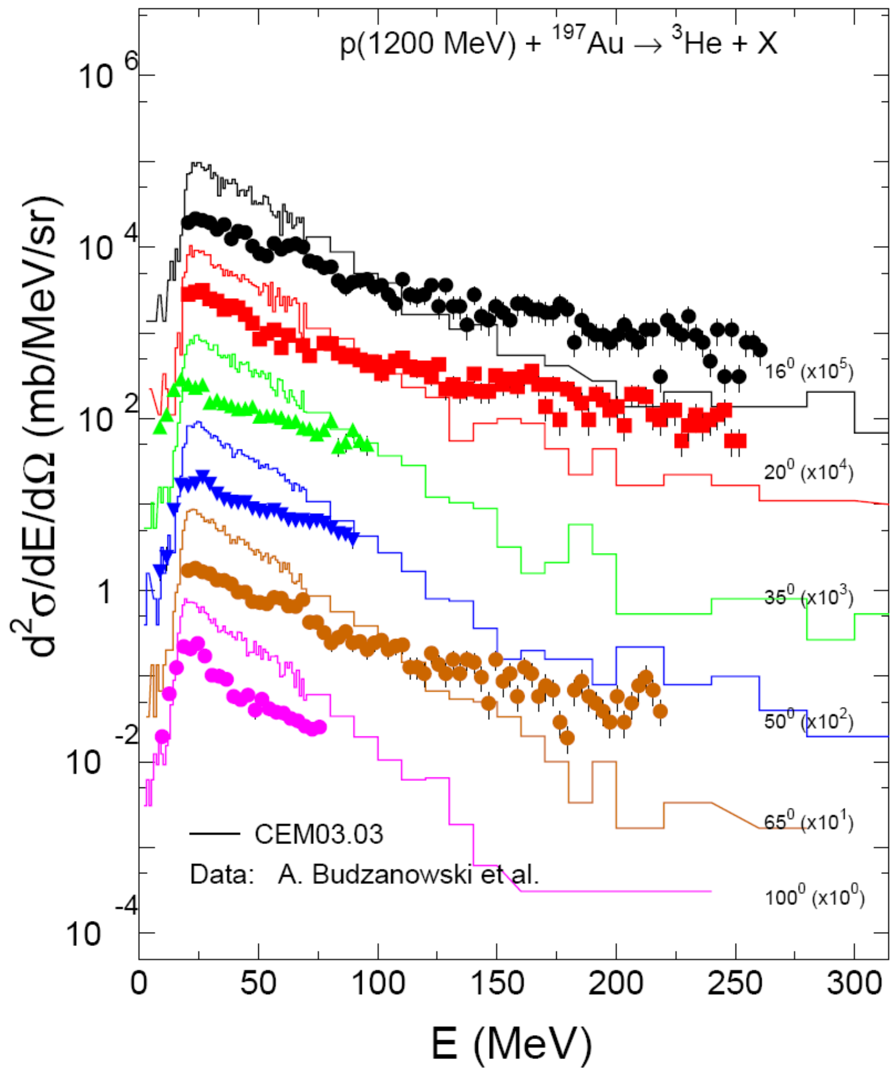


Gudima, 4-8 May 2009, Vienna

Benchmarking the CEM03.03 event generator

^{3}H and ^{3}He Spectra

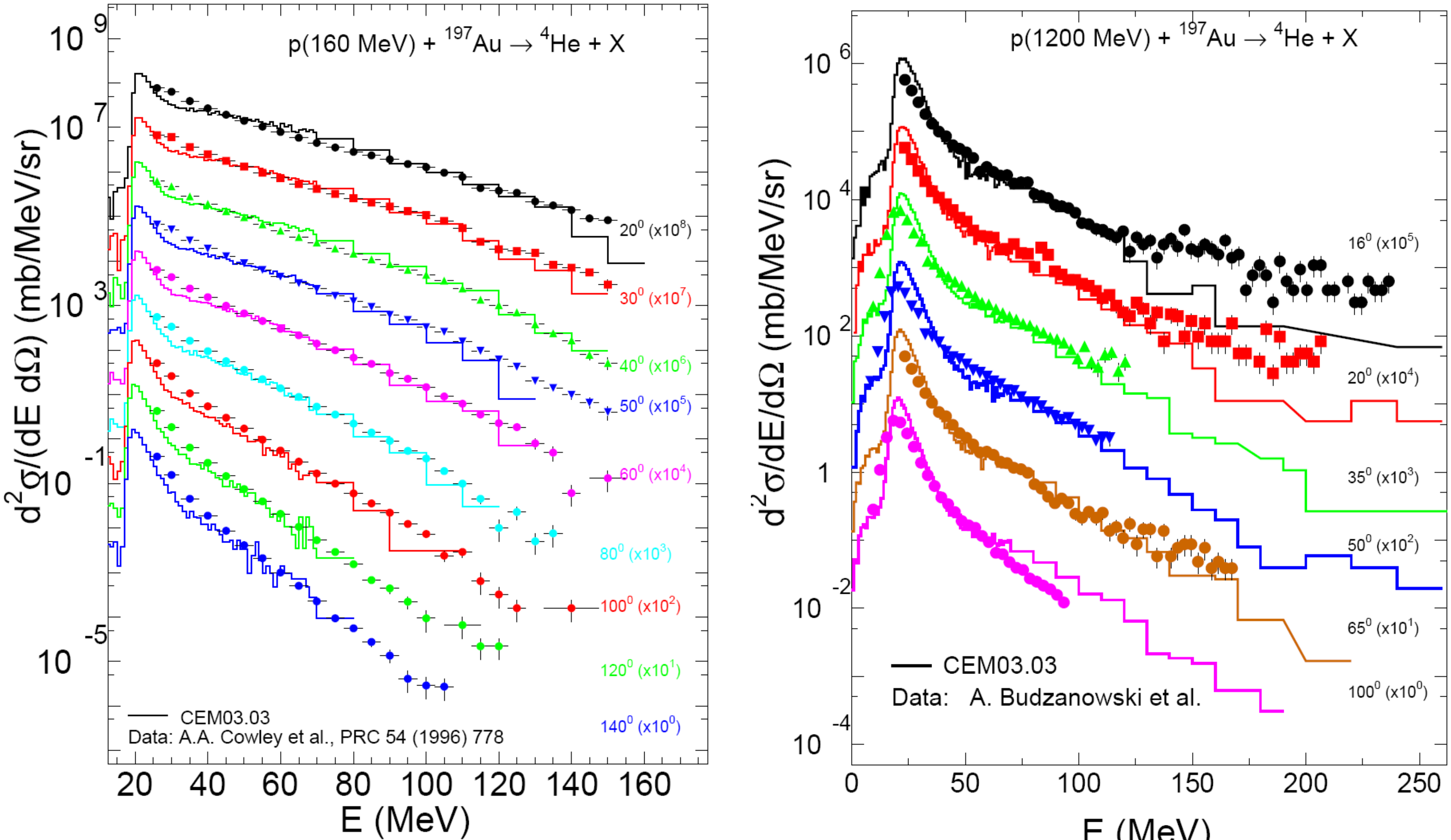




Gudima, 4-8 May 2009, Vienna

Benchmarking the CEM03.03 event generator

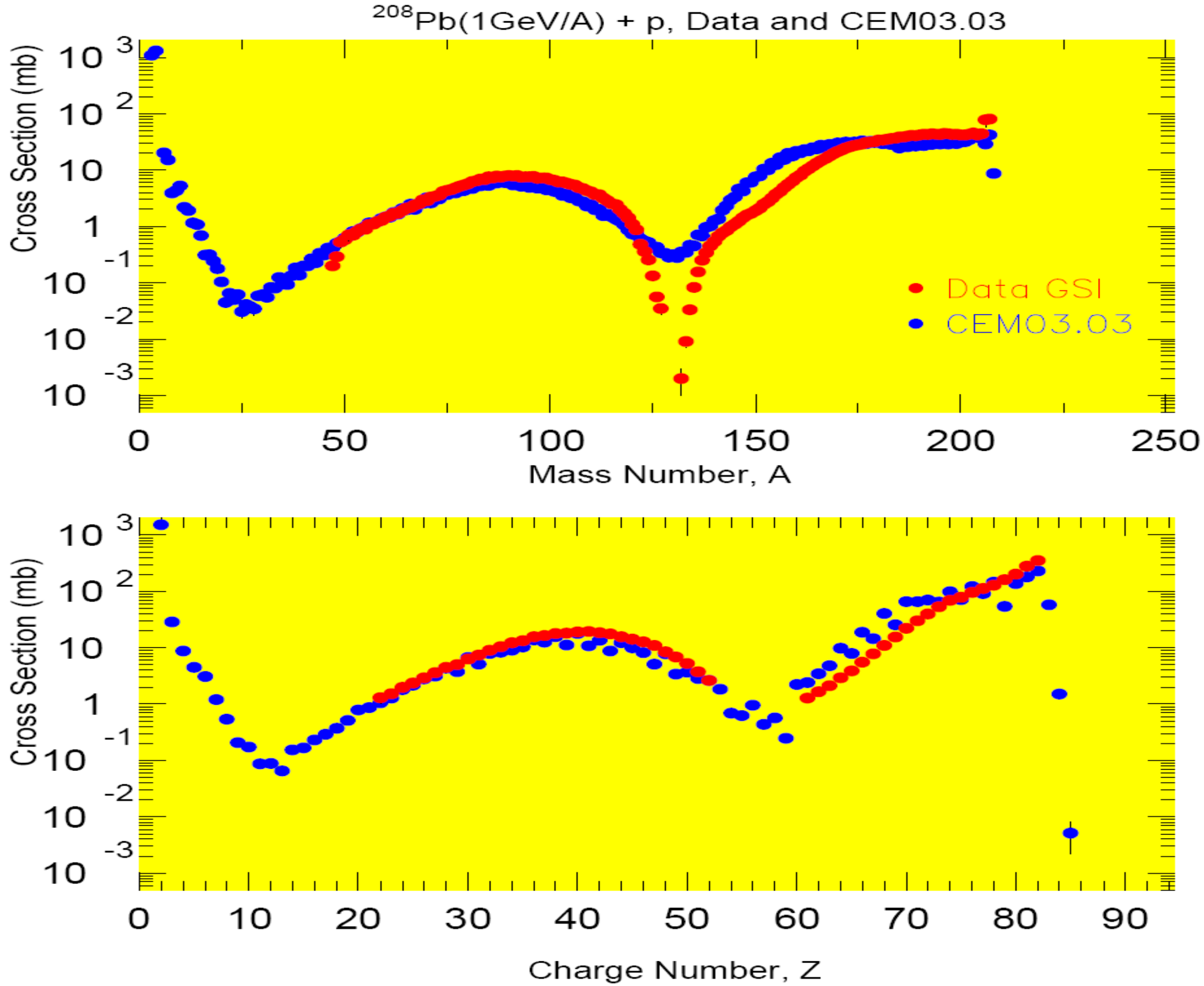
^{4}He spectra



Gudima, 4-8 May 2009, Vienna

Benchmarking the CEM03.03 event generator

Isotope production



Gudima, 4-8 May 2009, Vienna

Summary

- The CEM03.03 is the latest version of code based on Cascade Exciton Model developed to describe nuclear reactions of interest to Spallation Applications;
- This latest version of our code 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 Organizers for inviting me to present this talk ; I am grateful to IAEA for financial support and kind hospitality!

- Thank you for attention