Heavy Ion Interactions

Beginners' FLUKA Course

Overview

The models

- DPMJET
- RQMD
- BME

Input options

- Beam definition
- Transport thresholds

Heavy ion interaction models in FLUKA - 1

E > 5 GeV/n

Dual Parton Model (DPM)
DPMJET-III (original code by R.Engel, J.Ranft and S.Roesler,
FLUKA-implemenation by T.Empl *et al.*)

~0.1 GeV/n < E < 5 GeV/n

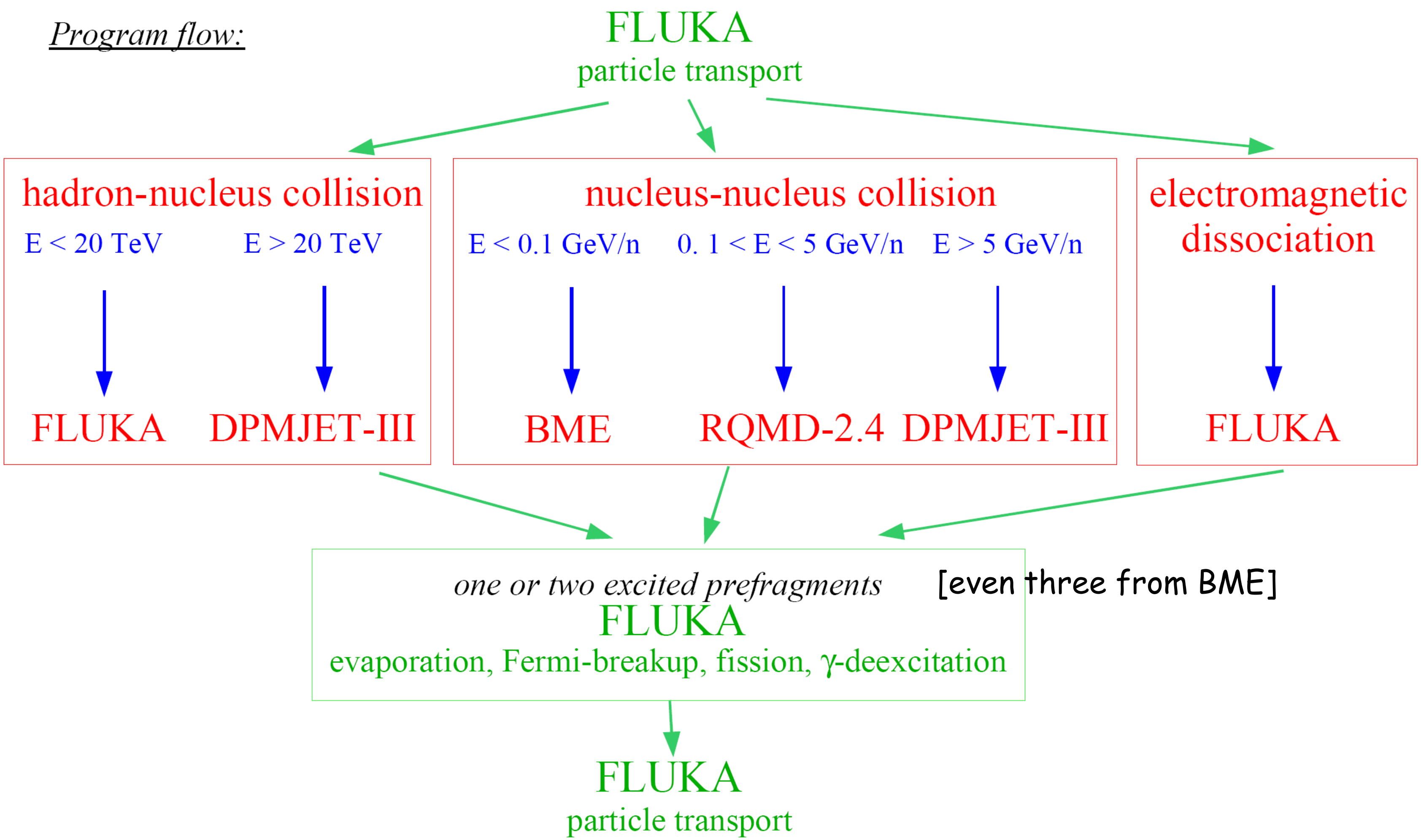
Relativistic Quantum Molecular Dynamics Model (RQMD)
RQMD-2.4 (original code by H.Sorge *et al.*,
FLUKA-implementation by A.Ferrari *et al.*)

E < ~0.1 GeV/n

Boltzmann Master Equation (BME) theory
BME (original code by E.Gadioli *et al.*,
FLUKA-implementation by F.Cerutti *et al.*)

Heavy ion interaction models in FLUKA - 2

<u>*Program flow:*</u>



DPMJET

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DPMJET – *Overview*

DPMJET = Dual Parton Model and JETs

Monte Carlo **event-generator** for the simulation of high-energy hadronic interactions

- hadron-hadron collisions,
  hadron-nucleus collisions,
  nucleus-nucleus collisions,
  photoproduction off nuclei (only Version III)

- energy range: 5 GeV/nucleon – 10^{11} GeV/nucleon
- programming language: Fortran77
- size of the code (Version III): about 90.000 lines
- authors: J. Ranft (Version II),
  R.Engel, J. Ranft, S. Roesler (Version III)

DPMJET – *Main steps of a high energy interaction*

1. Interaction of high-energy nuclei

→ individual nucleon-nucleon scatterings

→ formation of »strings« between valence and sea partons (quarks, gluons)

2. Hadronization process

→ creation of hadrons / resonances

3. Intranuclear cascade

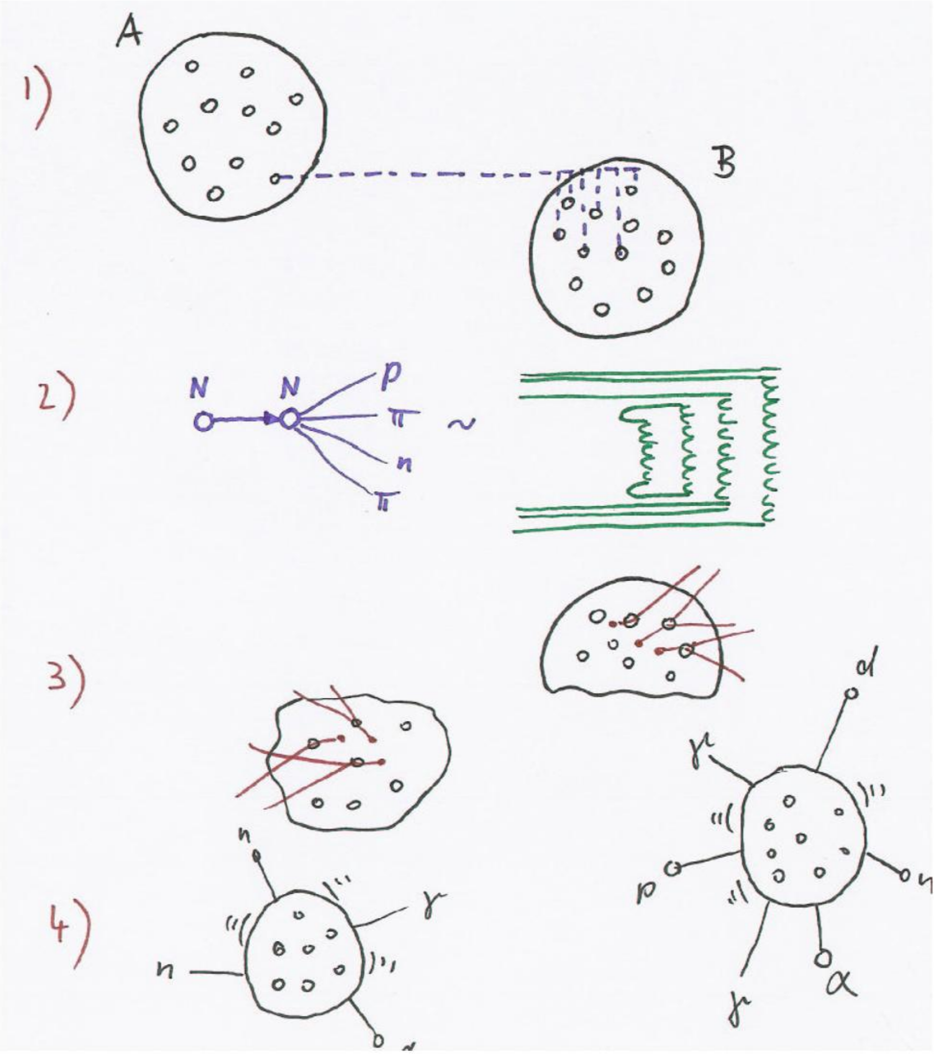
→ low-energy interactions of hadrons in spectator nuclei

4. Fragmentation of excited spectator nuclei

→ evaporation of light fragments (e.g., p, n, d, ^{3}H, ^{3}He, ^{4}He,..),

→ fragmentation, fission

→ production of residual nuclei



DPMJET – *The Gribov-Glauber formalism*

Fundamental idea: nucleus-nucleus collision expressed in terms of individual nucleon-nucleon interactions

- nucleus-nucleus

  - *total cross section* $$\sigma_{AB}^{tot}(s) = 4 \int d^2\vec{B}\, \Im[A_{AB}(s,\vec{B})]$$

  - *elastic cross section* $$\sigma_{AB}^{el}(s) = 4 \int d^2\vec{B}\, \left|A_{AB}(s,\vec{B})\right|^2$$

  - *scattering amplitude* $$A_{AB} = \frac{i}{2}\left[1 - \exp(\chi_{AB})\right]$$

  eikonal function $$\chi_{AB} = \sum_{k,l} \chi_{N_k N_l}$$

- nucleon-nucleon

  - *scattering amplitude* $$a_{N_k N_l} = \frac{i}{2}\left[1 - \exp(\chi_{N_k N_l})\right]$$

DPMJET – *Intranuclear cascade and fragmentation*

- nuclear model : - Fermi-gas of nucleons in potential well
  - nuclear densities: shell model ($A \leq 18$)
  Wood-Saxon ($A>18$)

- hadrons are followed in space and time on straight trajectories

- hadrons may re-interact after certain formation-time
  (assume local nuclear density and vacuum cross sections)

- calculation of excitation energies (in AA interactions for both spectators)

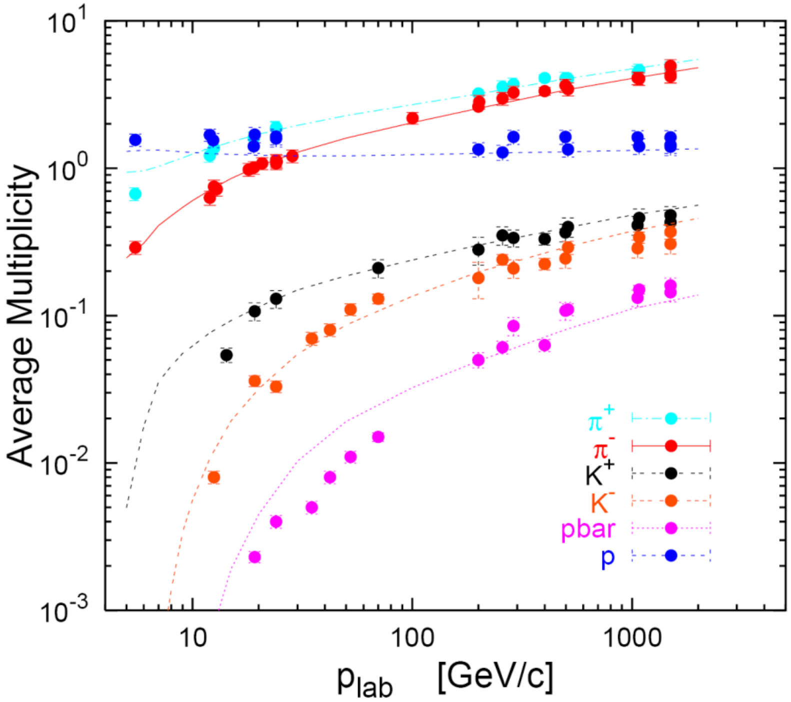
Note: *DPMJET has its own implementation of intranuclear cascades. It is similar in its fundamental ideas to that one of FLUKA but is much more simplified.*

- fragmentation by
  - nuclear evaporation
  - Fermi-breakup
  - high-energy fission
  - γ-deexcitation

  FLUKA

DPMJET – *Comparison to data (hadron-hadron)*

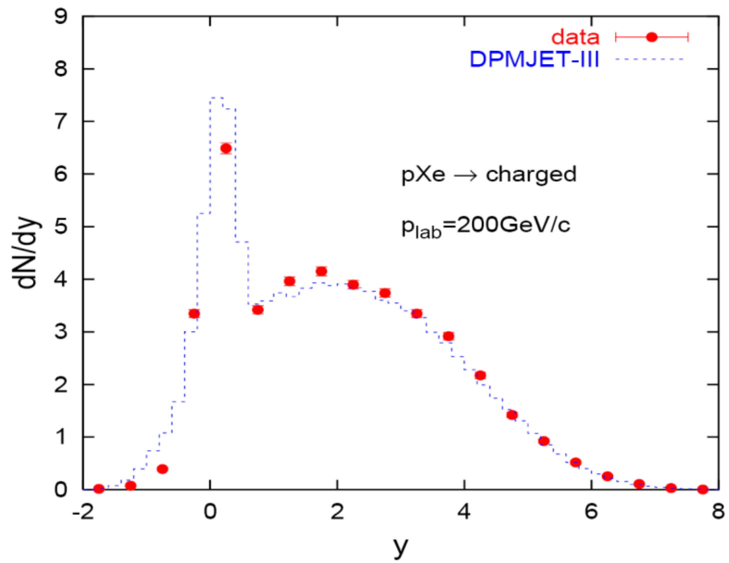
proton - proton

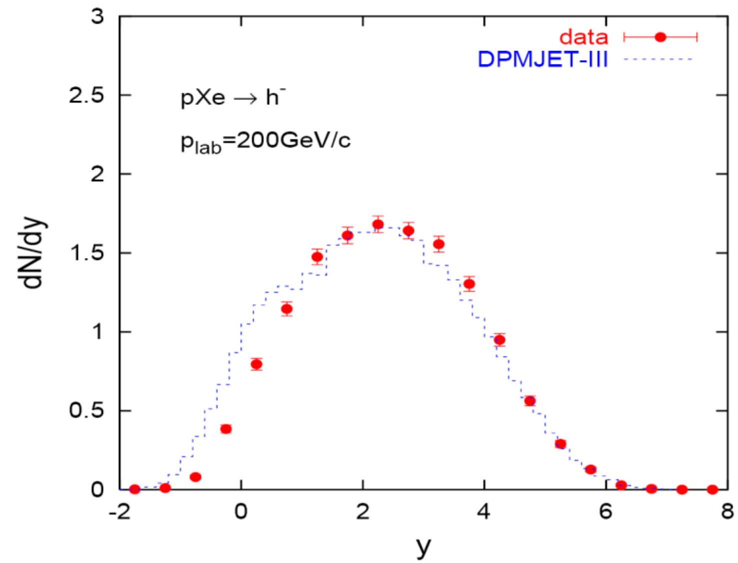


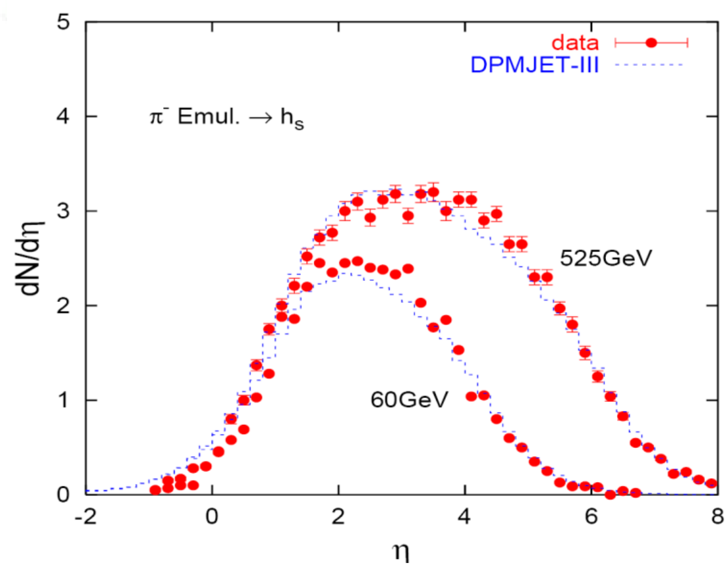
proton - proton, E_{lab} = 200GeV

	Exp.	DPMJET-III
charged	7.69 ± 0.06	7.64
neg.	2.85 ± 0.03	2.82
p	1.34 ± 0.15	1.26
n	0.61 ± 0.30	0.66
π^+	3.22 ± 0.12	3.20
π^-	2.62 ± 0.06	2.55
K^+	0.28 ± 0.06	0.30
K^-	0.18 ± 0.05	0.20
Λ	0.096 ± 0.01	0.10
$\bar{\Lambda}$	0.0136 ± 0.004	0.0105

DPMJET – *Comparison to data (hadron-nucleus)*

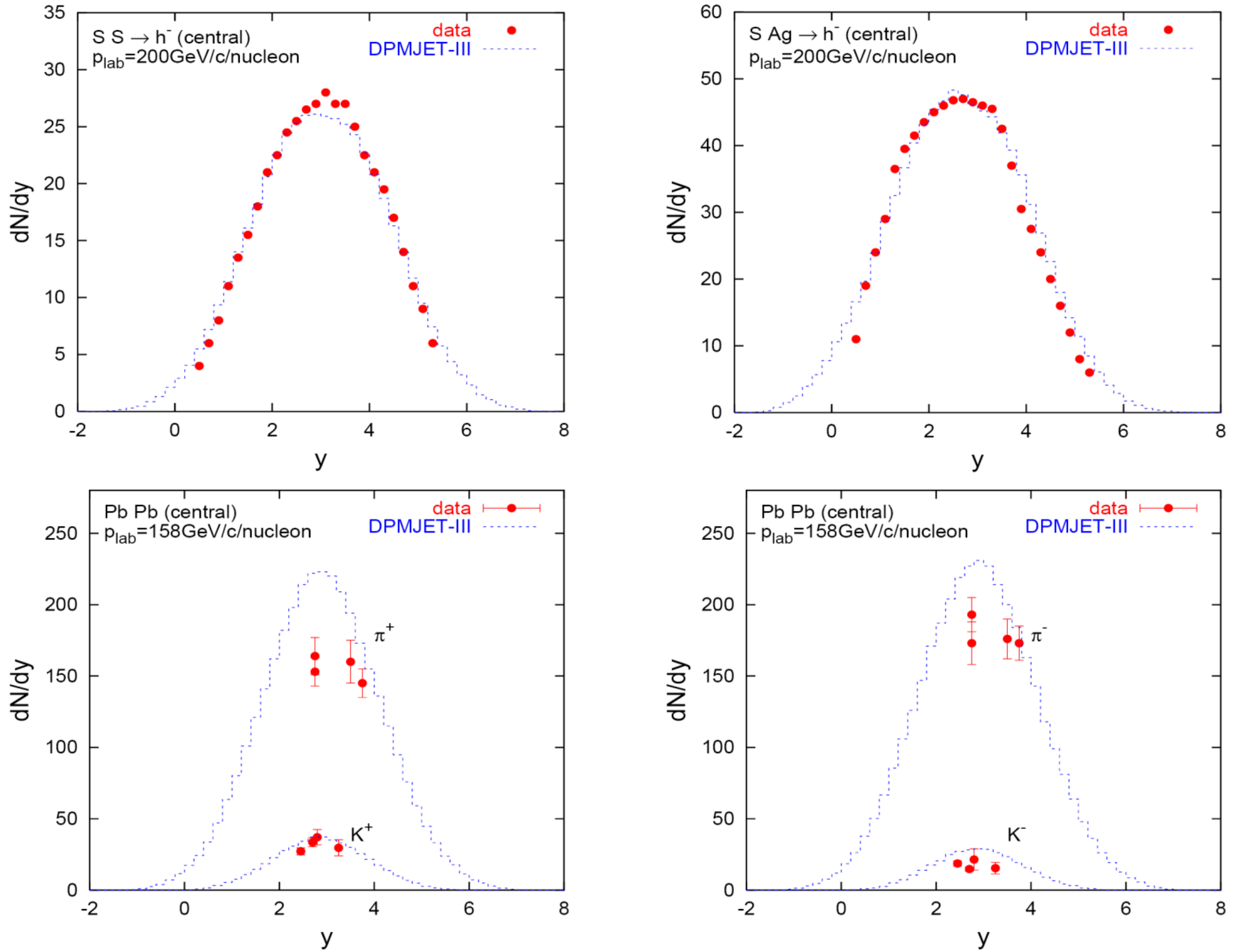




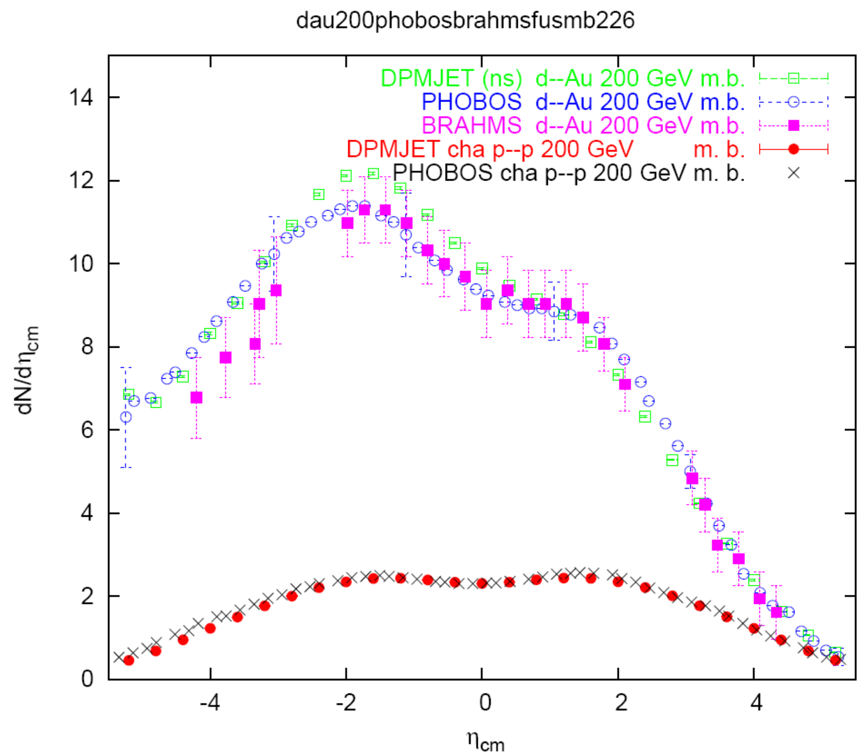


		Exp.	DPMJET-III
14.6 GeV	p Al	1.57 ±0.23	1.52
	p Au	2.15 ±0.33	1.92
200 GeV	p S	5.0 ± 0.2	4.98
	p Xe	6.84 ±0.13	6.67
360 GeV	p Al	6.8 ±0.6	5.87
	p Au	8.9 ±0.4	8.77

DPMJET - *Comparison to data (nucleus-nucleus)*



DPMJET – *Comparison to data (nucleus-nucleus)*

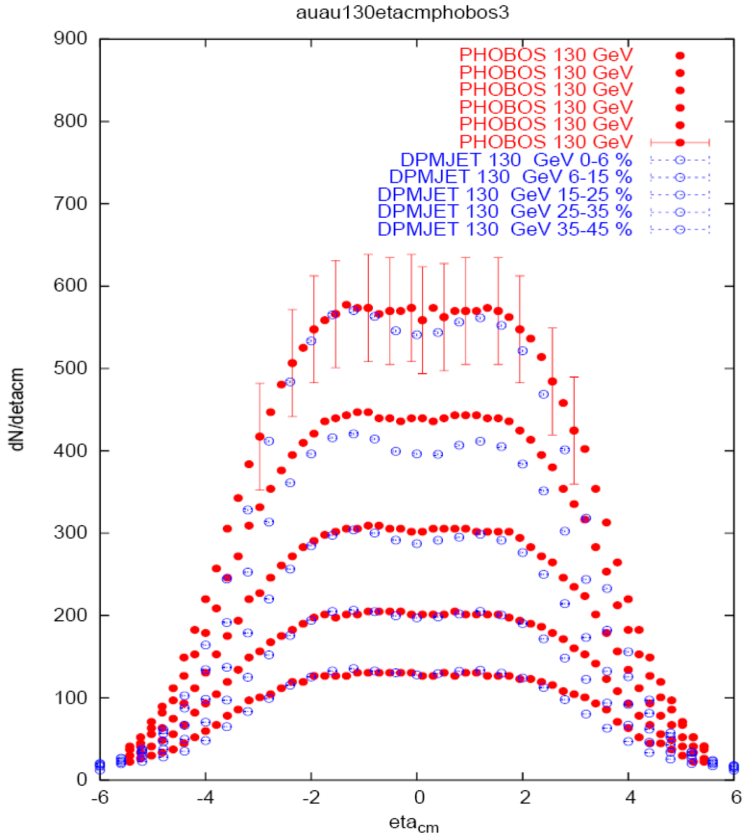


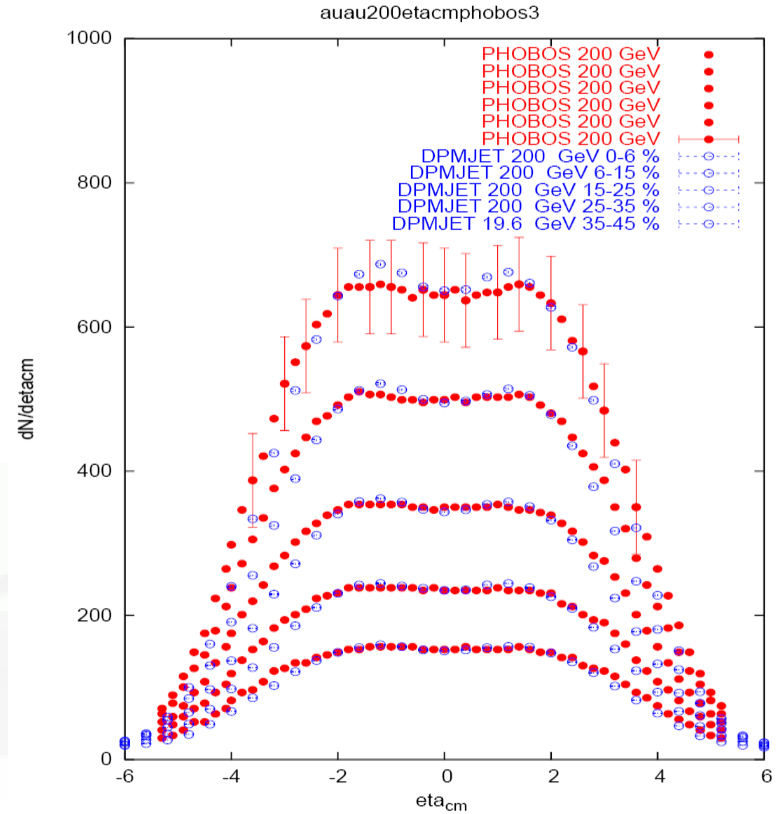
Pseudorapidity distribution of charged hadrons produced in minimum bias d-Au and p-p collisions at a c.m. energy of 200GeV/A.

Exp. data: BRAHMS- and PHOBOS-Collaborations

J.Ranft, in Proceedings of the Hadronic Shower Simulation Workshop, CP896, Batavia, Illinois (USA), 6-8 September 2006

DPMJET – *Comparison to data (nucleus-nucleus)*





Pseudorapidity distribution of charged hadrons produced in Au-Au collisions at a c.m. energy of 130GeV/A (left) and 200GeV/A (right) for different ranges of centralities.

Exp. data: PHOBOS-Collaboration

J.Ranft, in Proceedings of the Hadronic Shower Simulation Workshop, CP896, Batavia, Illinois (USA), 6-8 September 2006

DPMJET – *Interface to FLUKA*

FLUKA

Initialization of DPMJET:
pre-computed cross sections and impact parameter distributions read in from data files
(complete matrix of projectile-target combinations up to A=246 and entire energy range)

Request: Single nucleus-nucleus interaction (A+A)

↓

Interface

↓

DPMJET

A+A ⟶ p, n, π^+, π^-, ..., excited prefragments

↓

Interface

↓

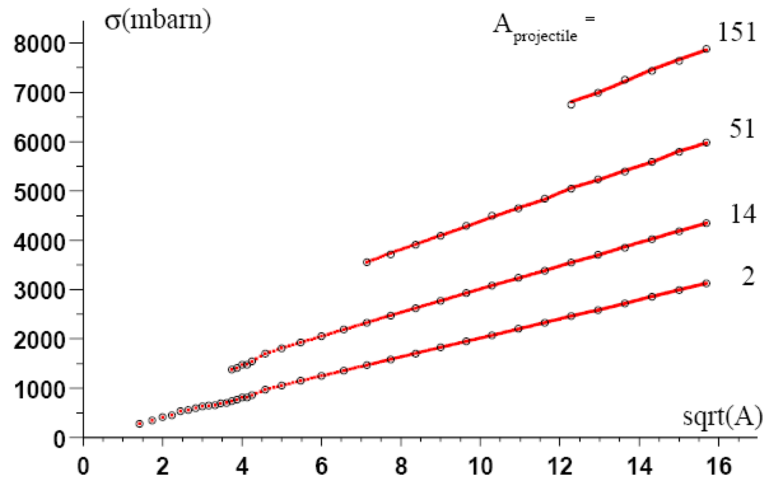
FLUKA

Evaporation, fragmentation, de-excitation of prefragments
Transport of produced hadrons

DPMJET – *Interface to FLUKA*

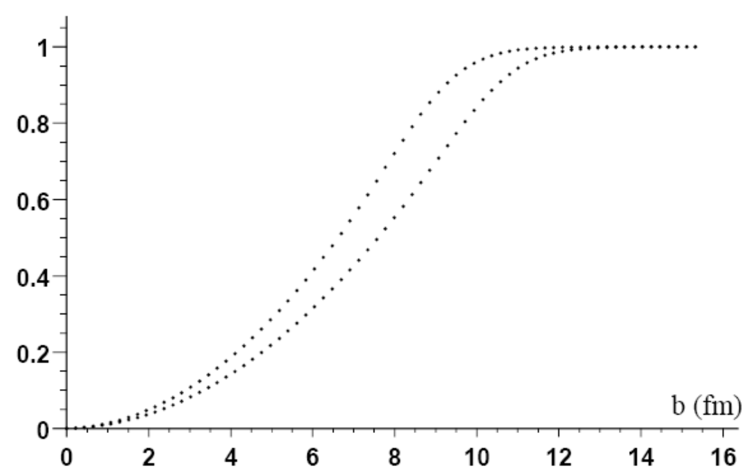
Examples for pre-initialised data:

Inelastic cross sections



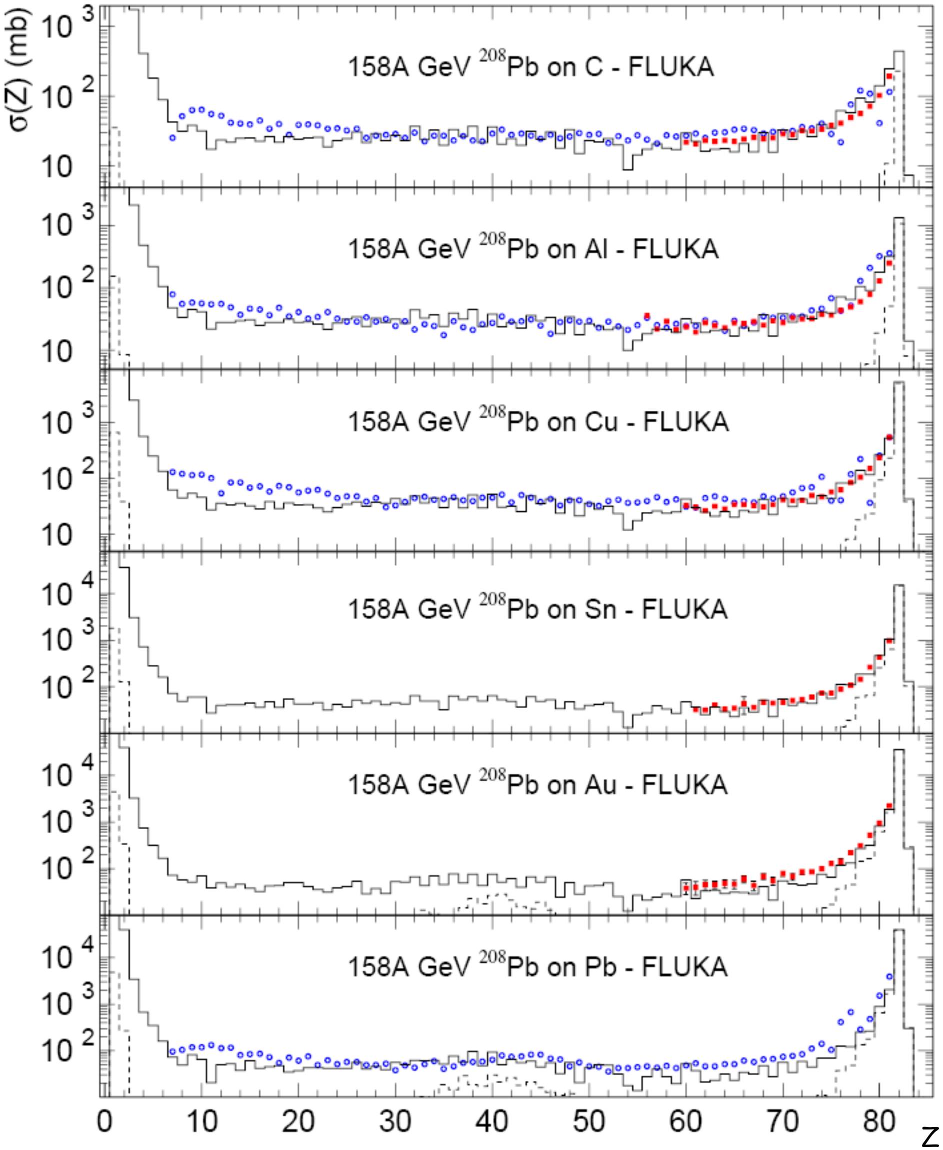
$E_{Lab} = 6.3 \times 10^9$ GeV/nucleon

Impact parameter distribution



e.g., for highest and lowest energy at one fixed projectile-target configuration

DPMJET – *FLUKA benchmarks*



Fragment charge cross sections for 158GeV/n Pb ions on various targets.
FLUKA: solid histogram(total)
dashed histogram (em diss.)
Exp. data: symbols
NPA662, 207 (2000),
NPA707, 513 (2002),
C.Scheidenberger *et al.* PRC

RQMD

E > 5 GeV/n

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E < 0.1 GeV/n
Boltzmann Master Equation (BME) theory
BME (original code by E.Gadioli et al.,
FLUKA-implementation by F.Cerutti et al.)

RQMD - *References*

interface to a suitably modified **RQMD model**

RQMD-2.4 (H. Sorge, 1998) was successfully applied

to relativistic A-A particle production over a wide energy range

[H. Sorge, Phys. Rev. **C 52**, 3291 (1995);

H. Sorge, H. Stöcker, and W. Greiner, Ann. Phys. **192**, 266 (1989)

and Nucl. Phys. **A 498**, 567c (1989)]

RQMD - *The original code*

The RQMD-2.4 code

INITIAL CONDITION two Fermi gases (projectile and target)

Fermi momentum $p_{F0} = \hbar \left(3\pi^2 \frac{A}{2V}\right)^{1/3}$ $V = (4/3)\,\pi \left(r_0 A^{1/3}\right)^3$ $r_0 = 1.12\,fm \Rightarrow \rho = 0.17\,\frac{nucl.}{fm^3}$

nucleon momentum $\boxed{p = p_{F0} \left(\frac{\rho(r)}{\rho_0}\right)^{\frac{1}{3}} \epsilon^{1/3}}$ $\epsilon \in [0, 1]$ random

$\phi = 2\pi\epsilon$ $\cos\theta = 1 - 2\epsilon$

$$p_x = p \sin\theta \cos\phi \quad - \left(\sum p_x\right)/A$$
$$p_y = p \sin\theta \sin\phi \quad - \left(\sum p_y\right)/A$$
$$p_z = p \cos\theta \quad - \left(\sum p_z\right)/A$$

so $\sum p_x = \sum p_y = \sum p_z = 0$

FINAL STATE

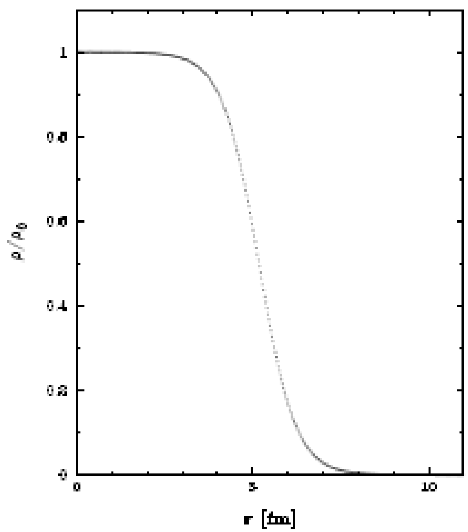
- $\left(p^0, p_x, p_y, p_z\right)$ for nucleons (and produced particles) in the LAB frame
- the spectators are marked
- no residue and fragment identification
- energy non-conservation issues, particularly when run in full QMD mode

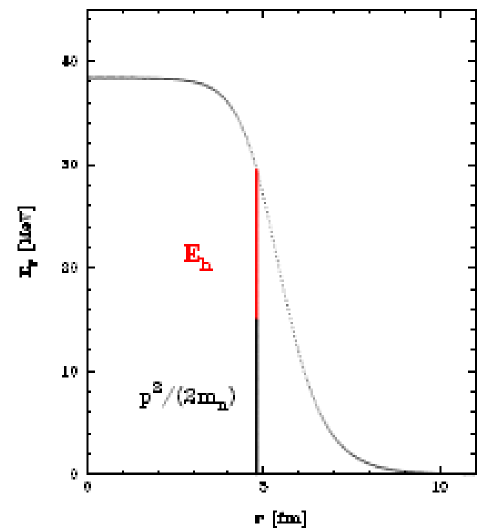
RQMD – *The interfaced code*

Implemented developments

- construct the **projectile- and target-like** nuclei by gathering *spectator* nucleons,

$$\text{assuming } E^*_{PL} = \sum_{pa.\ p} E_h \qquad (TL)$$





$$\rho(r) \propto \left(1 + \exp\left(\frac{r-R}{a}\right)\right)^{-1}$$

$$R = 1.19\,A^{1/3} - 1.61\,A^{-1/3}\ fm \qquad a = 0.52\ fm$$

$$E_h = \frac{1}{2m_n}\left\{\left[p_{F0}\left(\rho(r)/\rho_0\right)^{1/3}\right]^2 - p^2\right\}$$

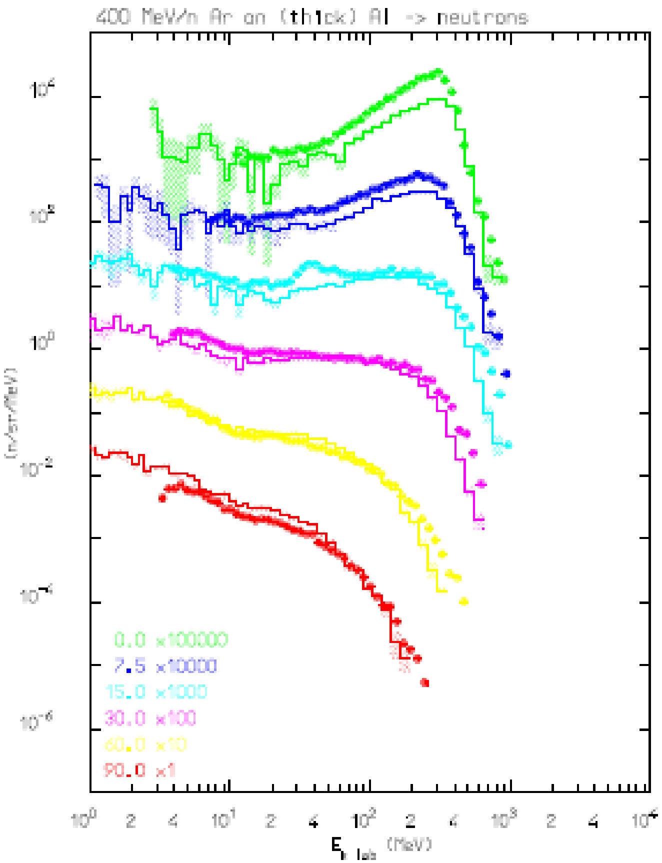
$$r, p\,(t=0)$$

- fix the remaining energy-momentum conservation issues taking into account **experimental binding energies**
- use the FLUKA evaporation/fission/fragmentation module

RQMD - *FLUKA benchmarks*

Double differential neutron yield

Ar ions

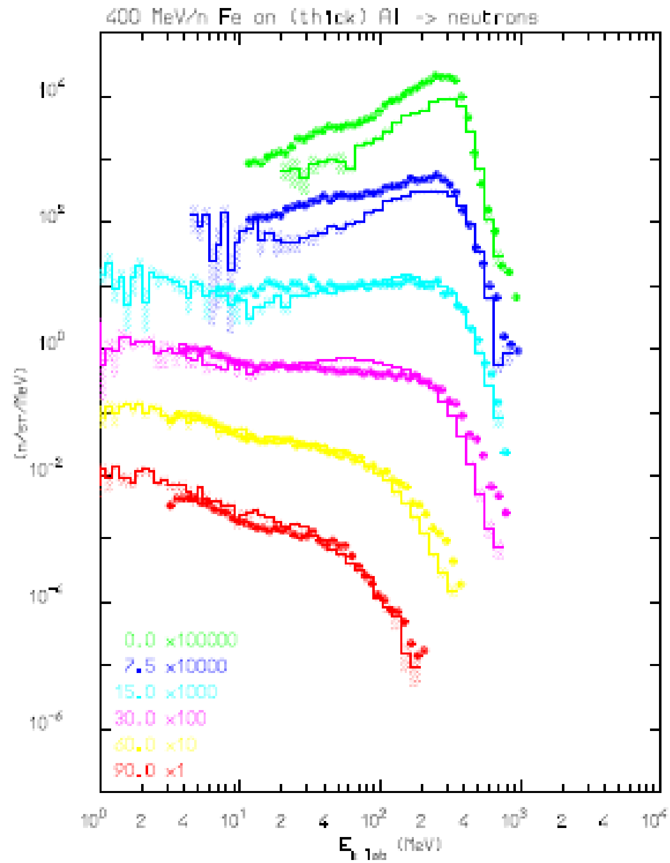


400 MeV/n

on *thick*

Al targets

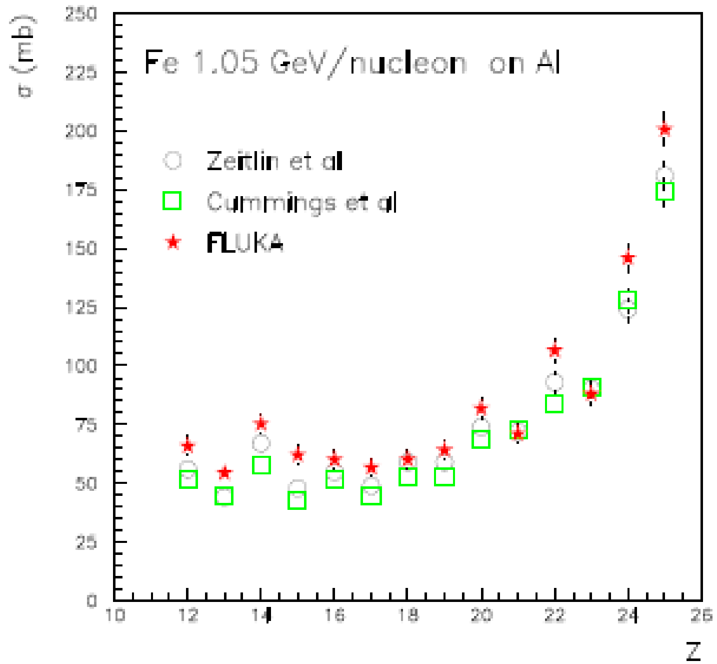
Fe ions

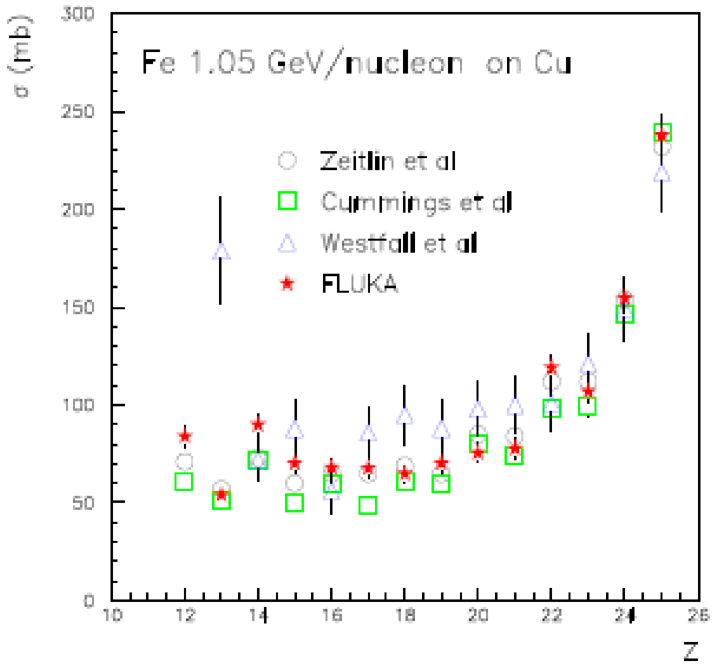


exp. data from T. Kurosawa *et al.*, Phys. Rev. **C 62**, 044615 (2000)

RQMD - *FLUKA benchmarks*

Fragment charge cross sections





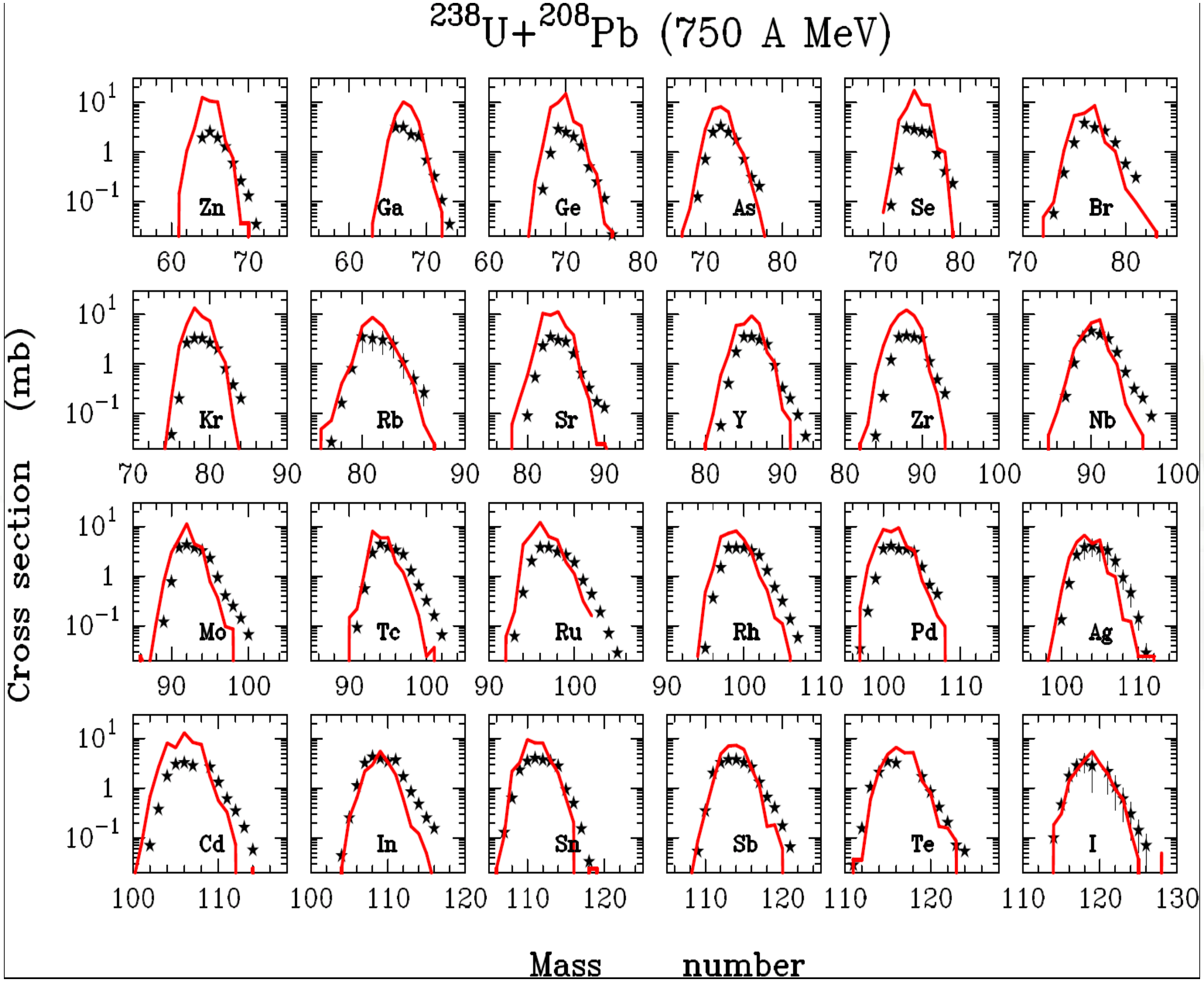
exp. data from C. Zeitlin *et al.*, Phys. Rev. **C 56**, 388 (1997),

J.R. Cummings *et al.*, Phys. Rev. **C 42**, 2508 (1990) (at 1.5 GeV/n),

G.D. Westfall *et al.*, Phys. Rev. **C 19**, 1309 (1979) (at 1.88 GeV/n)

RQMD - *FLUKA benchmarks*

Isotopic distributions of fragmentation products



fission products excluded like in the experimental analysis

exp. data (stars) from J. Benlliure, P. Armbruster *et al.*, Eur. Phys. J **A 2**, 193 (1998)

BME

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BME - *References*

interface to a Monte Carlo code

founded on the BME theory (E. Gadioli et al.)

[M. Cavinato *et al.*, Nucl. Phys. **A 679**, 753 (2001),

M. Cavinato *et al.*, Phys. Lett. **B 382**, 1 (1996)]

BME - *The interfaced code*

two different main reaction paths have been adopted:

1. COMPLETE FUSION

$P_{CF}=\sigma_{CF}/\sigma_R$

composite nucleus formation

2. PERIPHERAL COLLISION

$P = 1 - P_{CF}$

three body mechanism with possible incomplete fusion
one nucleon break-up and possibly transfer (at high *b*)
pickup/stripping (for asymmetric systems at low *b*)

pre-equilibrium de-excitation of the produced fragment(s)
according to the BME theory (where available)
or the PEANUT exciton model → *NB interface to PEANUT pre-eq not yet distributed!*

FLUKA evaporation/fission/fragmentation/gamma de-excitation

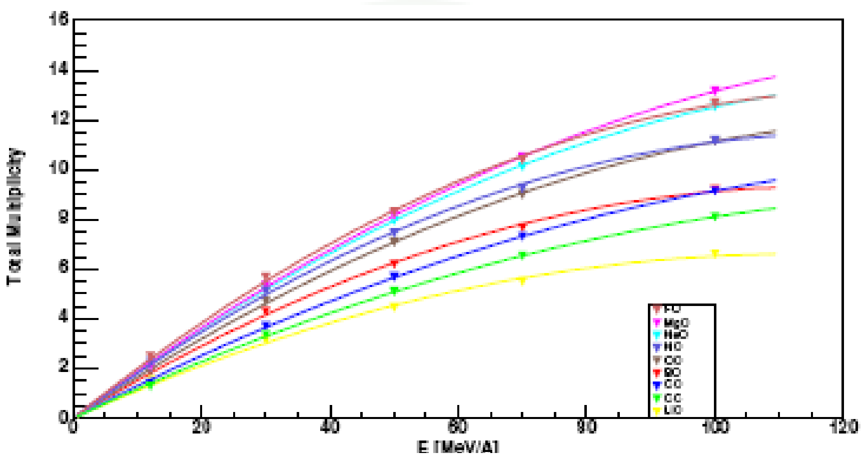
BME – *The database for the pre-equilibrium emissions*

In order to get the multiplicities of the pre-equilibrium particles and their double differential spectra, the BME theory is applied to several representative systems at different bombarding energies and the results are parameterized.

^{16}**O** + ^{6}Li, ^{8}Li, ^{8}B, ^{10}B, ^{12}C, ^{14}N, ^{16}O, ^{19}F, ^{20}Ne, ^{24}Mg, ^{27}Al, ^{56}Fe, ^{197}Au

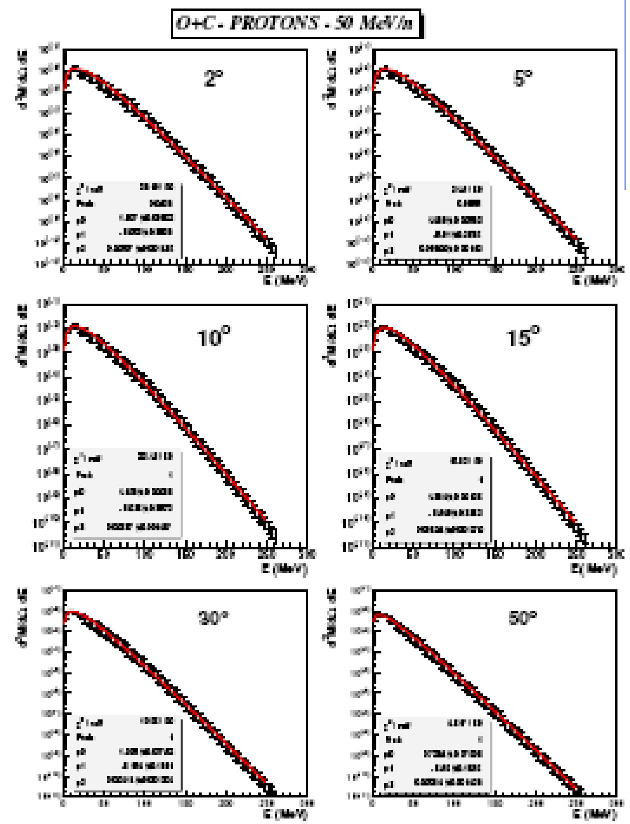
^{12}**C** + ^{8}Li, ^{8}B, ^{12}C, ^{27}Al, ^{40}Ca

@ 12, 30, 50, 70, 100 MeV/n



total multiplicity

$$M = P_1 E_{nucl} - P_2 E_{nucl}^2$$



energy spectra

$$d^2M/(dEd\Omega) = E^{P_0(\theta)} \exp(-P_1(\theta) - P_2(\theta)E)$$

Work is ongoing to extend it to more massive systems, i.e.

^{40}Ca + ^{120}Sn ^{56}Fe + ^{28}Si, ^{40}Ca, ^{48}Ca, ^{120}Sn

and consequently review the fitting functions
and the extrapolation recipes over a significantly larger mass range

BME – *Theoretical framework*

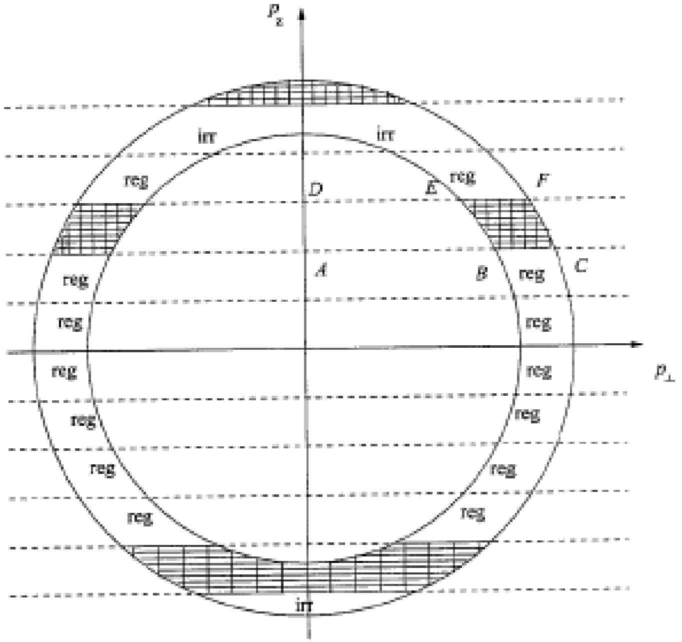
Calculation of preequilibrium for the composite nucleus

proton and neutron momentum spaces divided into bins

$$\left\{(p_x, p_y, p_z) : p_z \in [p_{zi}, p_{zi} + \Delta p_z),\ \varepsilon = (2m)^{-1}\left(p_x^2 + p_y^2 + p_z^2\right) \in [\varepsilon_i, \varepsilon_i + \Delta\varepsilon)\right\}$$

(**Z** is the beam direction)

of volume $2\pi m\, \Delta\varepsilon\, \Delta p_z$



BME - *Theoretical framework*

The BME system

$$N_i = n_i \, g_i$$

nucleon number (N_i), occupation probability (n_i), number of states in bin i (g_i)

$$\frac{d(n_i^\pi g_i^\pi)}{dt} = \sum_{jlm} [\omega_{lm\to ij}^{\pi\pi} g_l^\pi n_l^\pi g_m^\pi n_m^\pi (1-n_i^\pi)(1-n_j^\pi)$$

$$-\omega_{ij\to lm}^{\pi\pi} g_i^\pi n_i^\pi g_j^\pi n_j^\pi (1-n_l^\pi)(1-n_m^\pi)]$$

$$+\sum_{jlm} [\omega_{lm\to ij}^{\pi\nu} g_l^\pi n_l^\pi g_m^\nu n_m^\nu (1-n_i^\pi)(1-n_j^\nu)$$

$$-\omega_{ij\to lm}^{\pi\nu} g_i^\pi n_i^\pi g_j^\nu n_j^\nu (1-n_l^\pi)(1-n_m^\nu)]$$

$$-n_i^\pi g_i^\pi \omega_{i\to i'}^\pi g_{i'}^\pi \delta(\varepsilon_i^\pi - \varepsilon_{i'}^\pi - \varepsilon_F^\pi - B^\pi) - \frac{dD_i^\pi}{dt}$$

BME – *Theoretical framework*

Multiplicity spectra

of emitted nucleons

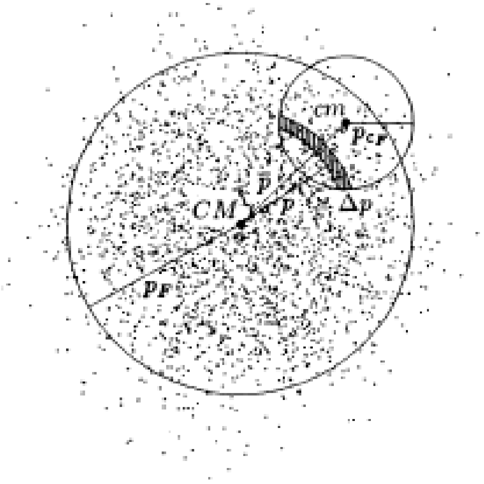
$$\frac{d^2M(\varepsilon',\theta)}{d\varepsilon'\,d\Omega} = \frac{1}{2\pi\sin\theta}\int_0^{t_{eq}} n(\varepsilon,\theta,t)\,\frac{\sigma_{inv}\,V}{V}\,\rho(\varepsilon',\theta)\,dt$$

of a cluster c

$$\frac{d^2M_c\,(E_c',\theta_c)}{dE_c'\,d\Omega} = \frac{R_c}{2\pi\sin\theta}\int_0^{t_{eq}} N_c\,(E_c\,,\theta_c,t)\,\frac{\sigma_{inv,c}\,V_c}{V}\,\rho_c\,(E_c',\theta_c)\;dt$$

$$N_c\,(E_c\,,\theta_c\,,t) = \prod_i\,(n_i^\pi\,(\varepsilon,\theta,t))^{P_i(E_c\,,\theta_c)Z_c}\cdot\prod_i\,(n_i^\nu\,(\varepsilon,\theta,t))^{P_i(E_c\,,\theta_c)N_c}$$

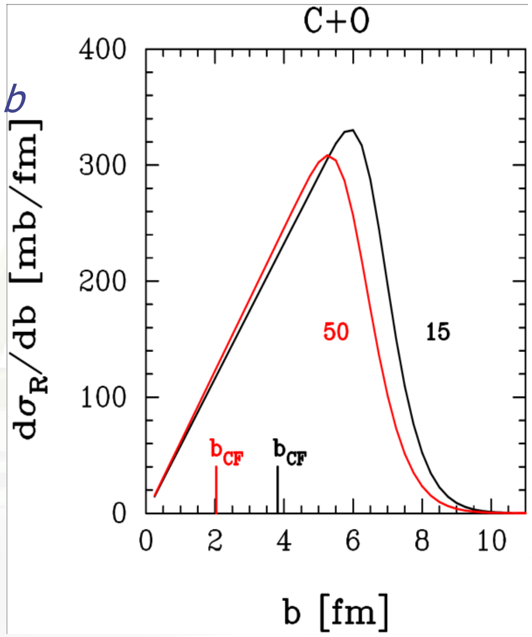
joint probability



BME - *Peripheral collisions*

We integrate the nuclear densities of the projectile and the target over their overlapping region, as a function of the impact parameter, and obtain a preferentially excited “middle source” and two fragments (projectile- and target-like). The kinematics is suggested by break-up studies.

i. selection of the *impact parameter b*



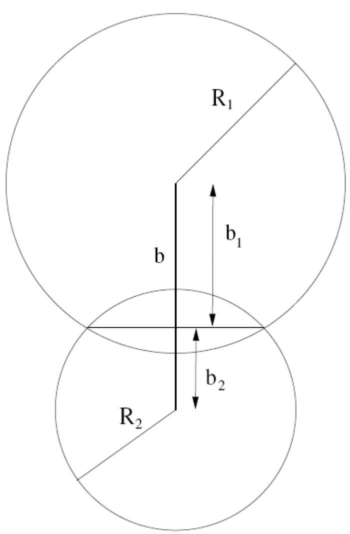
ii. kinematics determination

θ_{PL} , θ_{TL} chosen according to $[d\sigma/d\Omega]_{cm} \sim \exp(-k\theta_{cm})$
θ_{MS} momentum conservation
p_{PL} , p_{TL} chosen according to a given energy loss distribution
p_{MS} momentum conservation
ϕ_{PL} free
ϕ_{TL} , ϕ_{MS} same reaction plane

PL

MS

TL



iii. excitation energy sharing

$$E^\star_{MS} = (A_{MS}/A_{tot})E^\star_{tot}\sum_{n=0}^{k}(1 - A_{MS}/A_{tot})^n$$

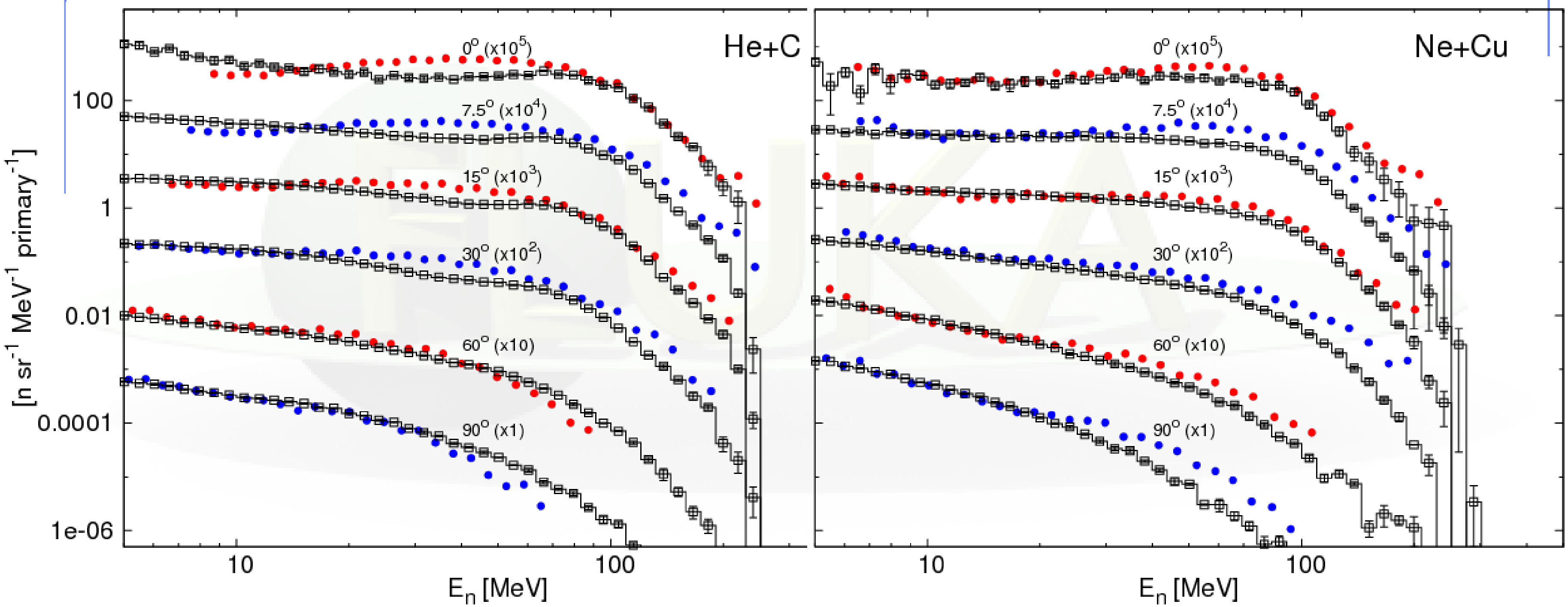
$$E^\star_{PL} = f(A_{PL}, A_{TL})\left(E^\star_{tot} - E^\star_{MS}\right)$$

forced on the experimental values in the discrete level region

$$E^\star_{TL} = \left(E^\star_{tot} - E^\star_{MS} - E^\star_{PL}\right)$$

BME - *Benchmarking*

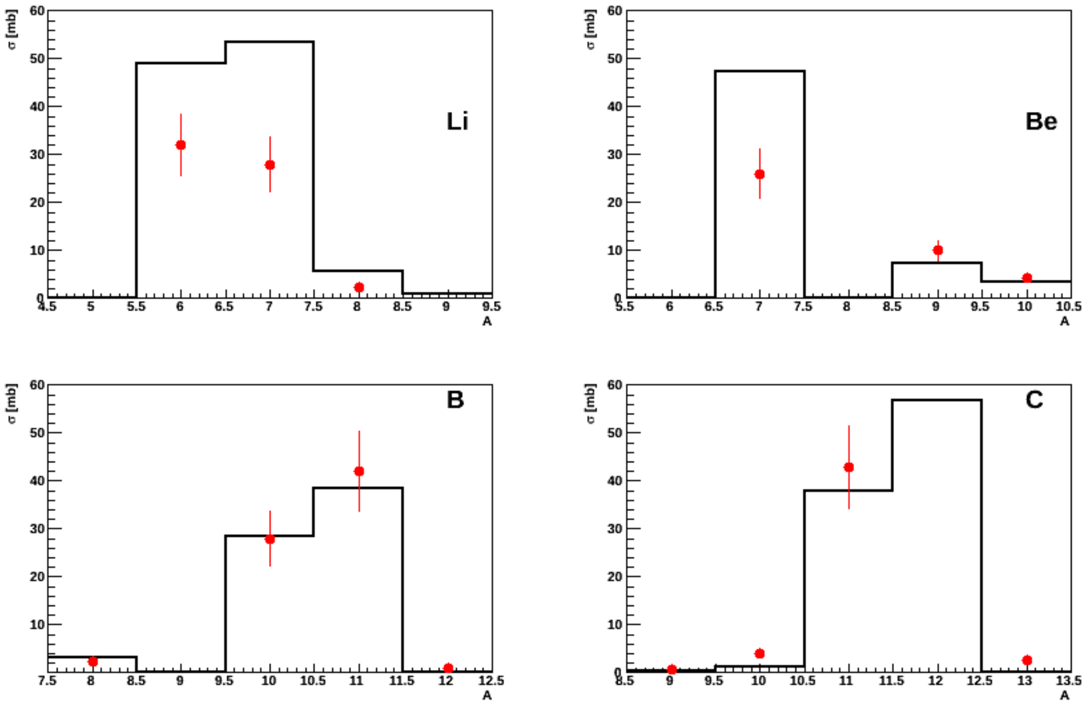
DOUBLE DIFFERENTIAL **NEUTRON** YIELDS FROM **100 MeV/n** BEAMS ON THICK TARGETS



FLUKA vs experimental data from T. Kurosawa, N. Nakao, T. Nakamura et al., Nucl. Sci. Eng. 132, 30 (1999)

BME – *Benchmarking*

ISOTOPE YIELDS
FROM C+C at **86 MeV/n**



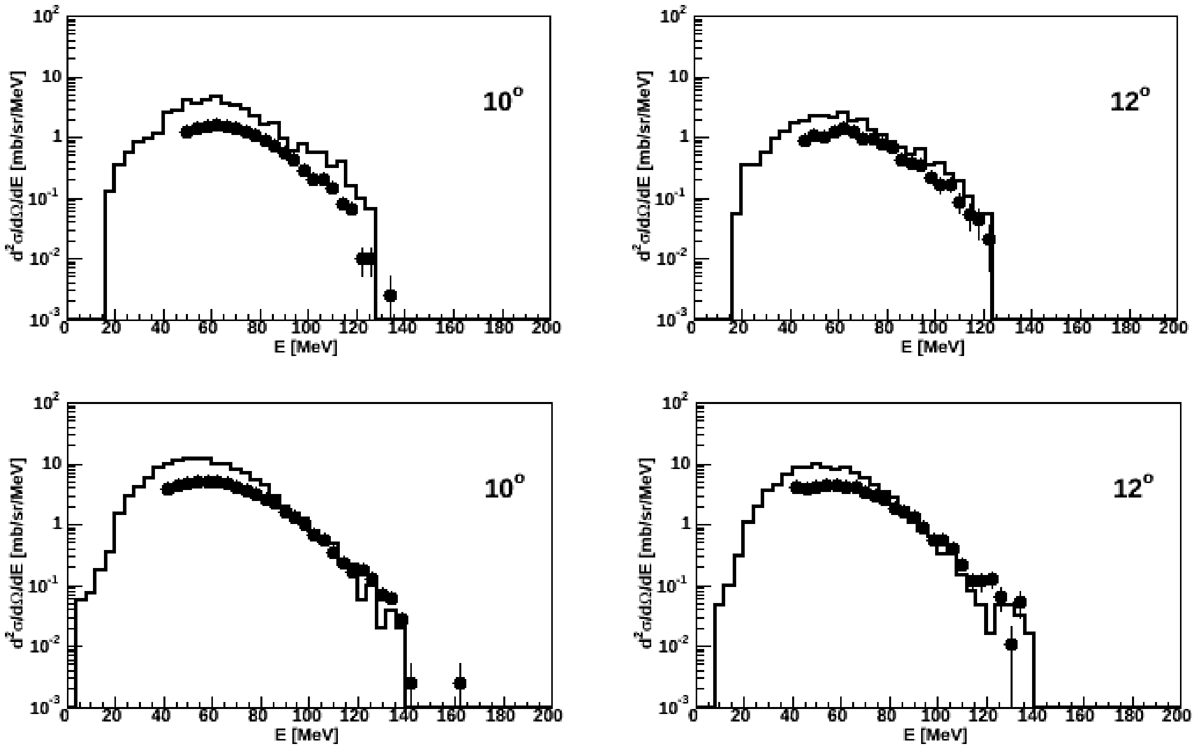
experimental data from H. Ryde, Physica Scripta T5, 114 (1983)

BME – *Benchmarking*

DOUBLE DIFFERENTIAL **FRAGMENT SPECTRA** FROM C+C at **13 MeV/n**

Fluorine

Oxygen



experimental data by courtesy of S. Fortsch et al., iThemba Labs, South Africa

Input options - 1

a) define momentum / energy

```
BEAM         -10.0      0.0      0.0      0.0      0.0      0.0HEAVYION
```

WHAT(1) > 0.0 : average beam momentum (GeV/*c*)
< 0.0 : average beam kinetic energy (GeV)

WHAT(2) beam momentum spread (GeV/*c*)

Note: for SDUM = HEAVYION units per nucleon (in fact per *nmu*)
for SDUM = 4-HELIUM, *etc.* per nucleus

WHAT(3)-WHAT(6) (as for any other particle)

SDUM = HEAVYION

also	**4-HELIUM**	alpha
	3-HELIUM	3-helium
	TRITON	tritium
	DEUTERON	deuterium

Input options - 2

b) define charge and mass *(required for* `BEAM/SDUM=HEAVYION`*)*

```
HI-PROPE        79.0      197.0       0.0        0.0        0.0        0.0
```

WHAT(1) = Atomic number Z of the heavy ion, Default: 6.0

WHAT(2) = Mass number A of the heavy ion, Default: 12.0

WHAT(3) = if < 0 isomeric state of the heavy ion

c) switch on heavy ion transport and interactions

```
IONTRANS        -2.0        (pleonastic in case of ion beams)
```

Note: **Don't forget** to link the DPMJET/RQMD event generators for enabling ion-ion interactions above 125MeV/n either using FLAIR or **`$FLUPRO/flutil/ldpmqmd`**
The BME event generator, covering the low energy range up to 150MeV/n (125MeV/n is the default threshold, that you can change through `PHYSICS/SDUM=DPMTHRES`), does not need to be linked since it's already embedded in the main FLUKA library

Input options - 3

Notes:

- The transport momentum threshold for ions ($p_{th,HI}$) is fixed to that of alphas ($p_{th,\alpha}$)

$$p_{th,HI} = p_{th,\alpha} \times m_{HI}/m_{\alpha} \quad (GeV/c)$$

- Unless the transport threshold for alphas is defined with a PART-THR card *(requiring GeV and not GeV per nucleon)* it is set equal to 10 MeV if `DEFAULTS=NEW-DEFA`.

- When the energy of an ion becomes lower than the transport threshold, and if such threshold is lower than 100 MeV/n, the ion is not stopped, but it is ranged out to rest

Input options - 4

Electromagnetic dissociation

```
PHYSICS          2.0       0.0       0.0       0.0       0.0       0.0EM-DISSO
```

WHAT(1) : flag for activating ion electromagnetic-dissociation

```
=< -1.0 : resets to default (no em-dissociation)
=   0.0 : ignored
=   1.0 : (default) no em-dissociation
=   2.0 : projectile and target em-dissociation activated
=   3.0 : projectile only em-dissociation activated
=   4.0 : target only em-dissociation activated
```

WHAT(2)-WHAT(6): not used