Perspectives and future for intranuclear-cascade and nuclear-de-excitation models

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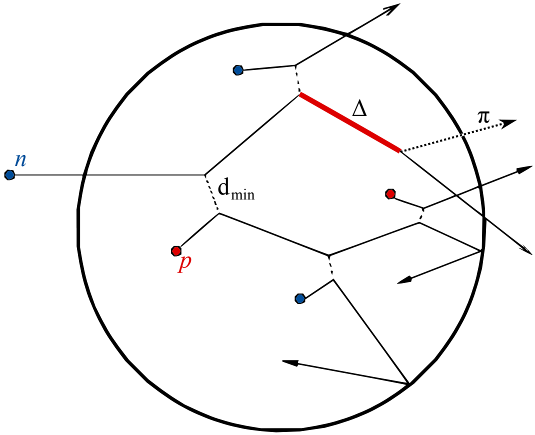
7th April 2011
30 years of strong interactions

Plan

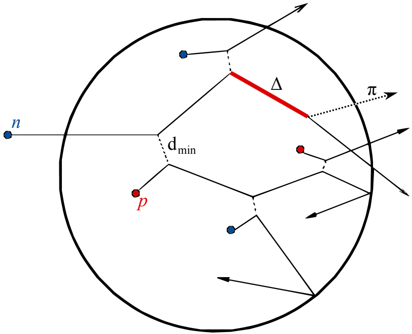
1. Intranuclear cascade
   - Principles
   - Application domain
2. Extensions of standard cascade
   - Exotic nuclei
   - Nucleus-nucleus collisions
3. Nuclear de-excitation
   - Spallation et multifragmentation
4. Conclusions

Intranuclear cascade



Serber
Phys. Rev. 72 (1947) 1114

Intranuclear cascade

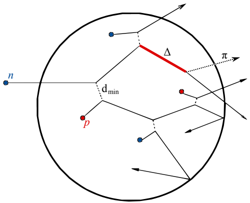


Features

- Binary collisions
  - Pauli principle!
- Reflection or transmission on the surface
- Excited remnant
  - Coupling with a de-excitation model

Binary collisions

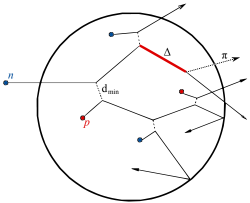
mean free path $>$ incoming wavelength



Binary collisions

mean free path $>$ incoming wavelength

$$\Lambda = \frac{1}{\rho_0 \, \sigma_{NN} \, f_{\mathrm{Pauli}}}$$



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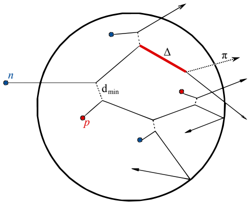
$$\Lambda = \frac{1}{\rho_0 \, \sigma_{NN} \, f_{\mathrm{Pauli}}} \qquad \lambda = \frac{h}{p_{\mathrm{lab}}}$$

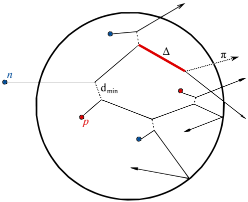


Binary collisions

mean free path $>$ incoming wavelength

$$\Lambda = \frac{1}{\rho_0 \, \sigma_{NN} \, f_{\mathrm{Pauli}}} \qquad \lambda = \frac{h}{p_{\mathrm{lab}}}$$

$$T_{\mathrm{lab}} > 150\text{–}200\ \mathrm{MeV}$$



Applicability of cascade models

For $T < 150$ MeV:

- ternary collisions
- interference among collisions
- quantum effects

Limited applicability of INC models

Applicability of cascade models

For $T < 150$ MeV:

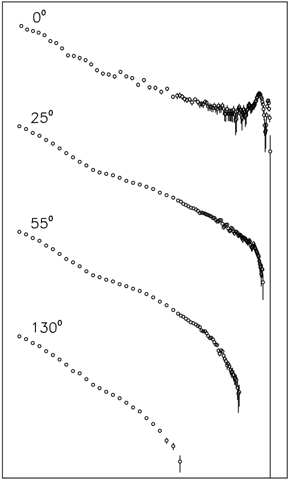
- ternary collisions
- interference among collisions
- quantum effects

Limited applicability of INC models

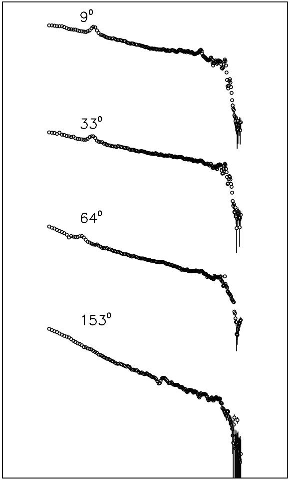
...right?

Quiz!

A



B

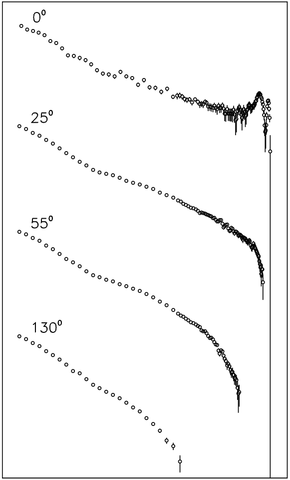


Pb(*p*,x)*n*

- 25 MeV
- 1600 MeV

Quiz!

1600 MeV



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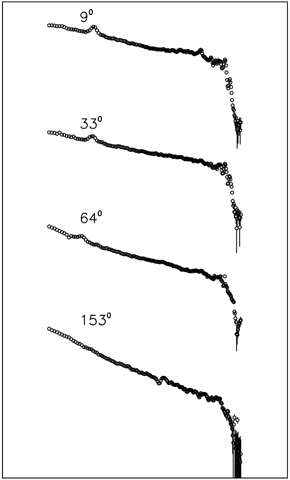

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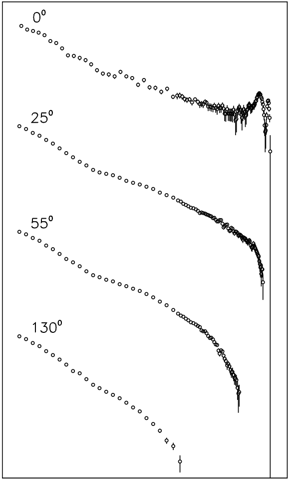
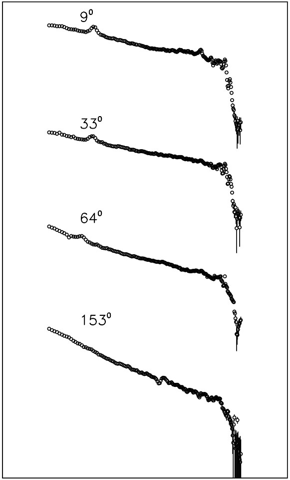


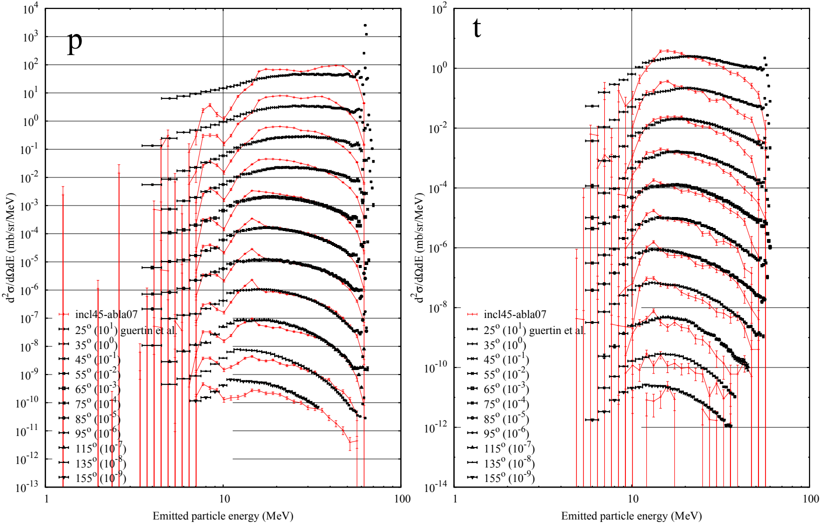
25 MeV



No traces of interference!

Physics changes smoothly with bombarding energy!

Surprise: Pb(*p*,x)*p*, Pb(*p*,x)*t*, 63 MeV



Guertin *et al.*

Eur. Phys. J. A23 (2005) 49

Model: INCL4.5+ABLA07

Quantum effects?

- Better than expected at low energy!
- Dynamics dominated by phase space?
- Details of the collisions are unimportant?

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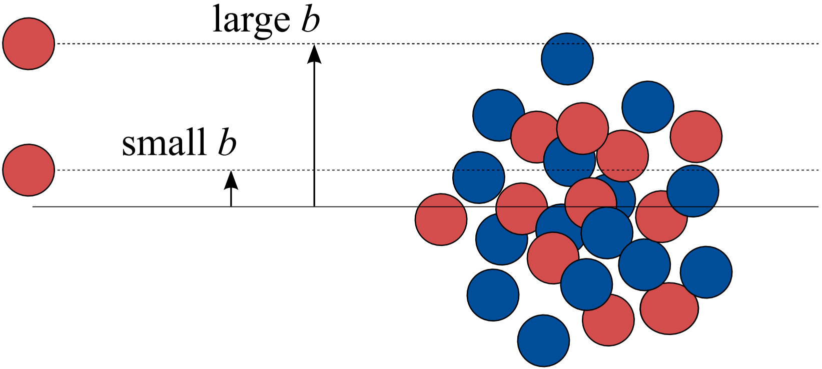
Whatever happened to quantum effects?

At very low energy. . .



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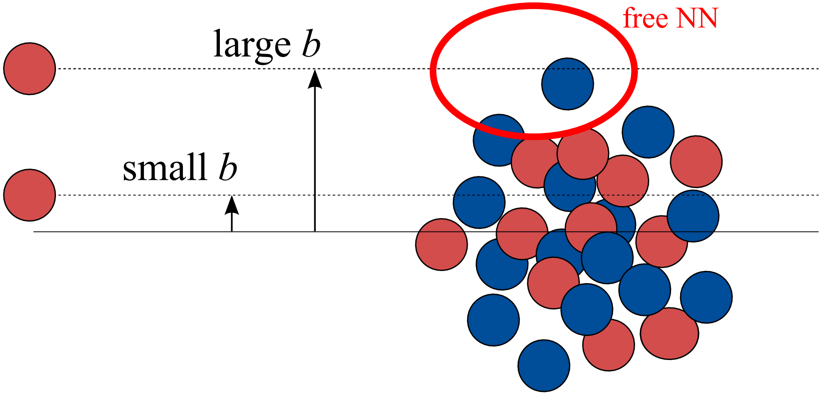

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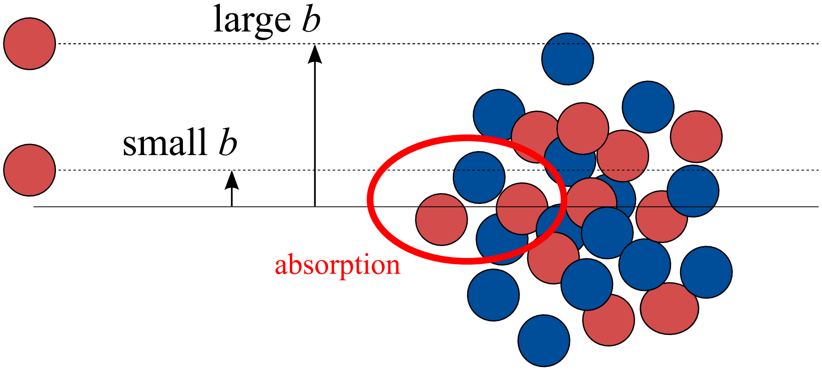

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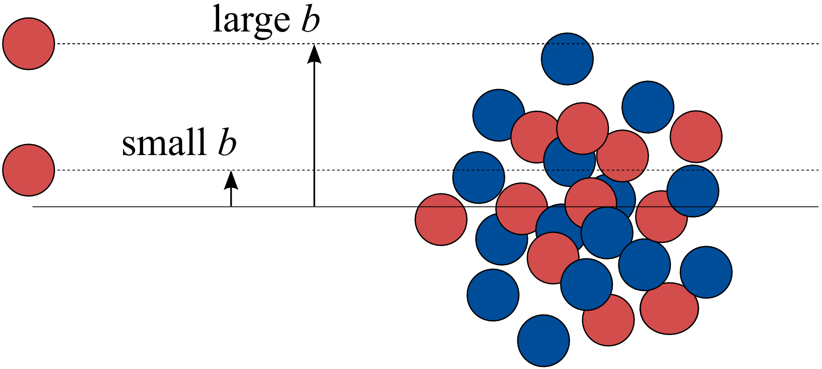


Dynamics plays a role in a small interval of impact parameters

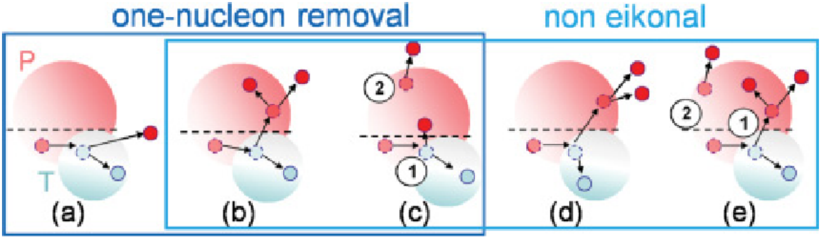
. . . but this is just hand-waving

Cascade works
but we don’t really understand why

Plan

Studying nuclear structure with INC

We can use INC to probe the structure of exotic nuclei



Louchart *et al.*
Phys. Rev. C83 (2011) 011601(R)

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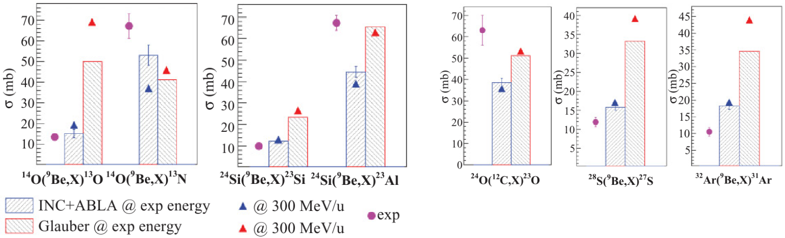

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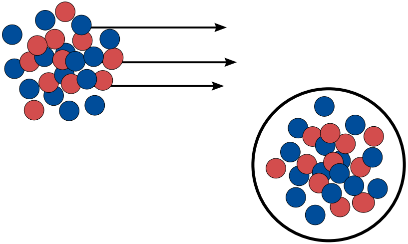
Goal

Describe nucleus-nucleus up to Si+Fe
$\sim$10 AGeV

TODO

- De-excitation of light nuclei
    - Fermi break-up
- Projectile–target symmetry



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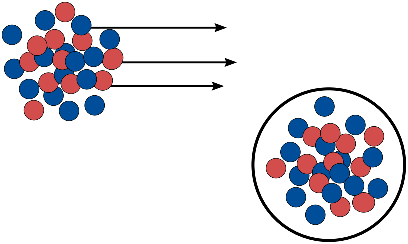
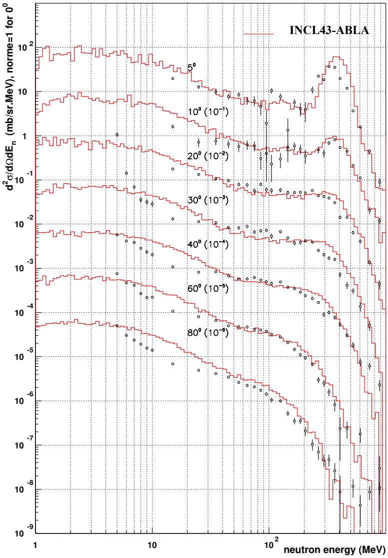


First approach

Direct extension of cascade (INCL4.5): projectile as a collection of free nucleons



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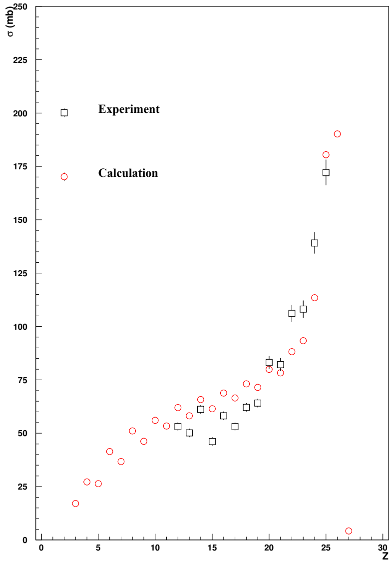
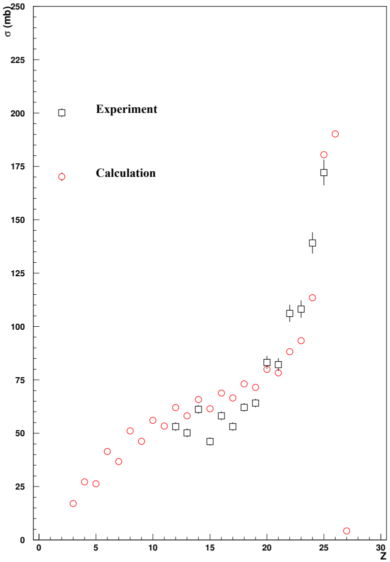
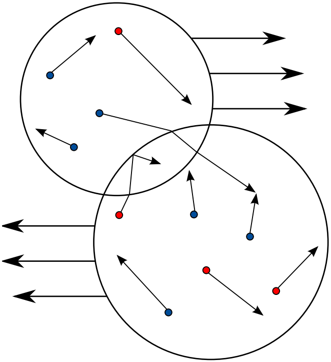


First approach

. . . but we cannot accurately describe projectile fragmentation!



Symmetric projectile–target treatment



Nucleus-nucleus extension

- projectile–target symmetric
- predict projectile- and target-related observables

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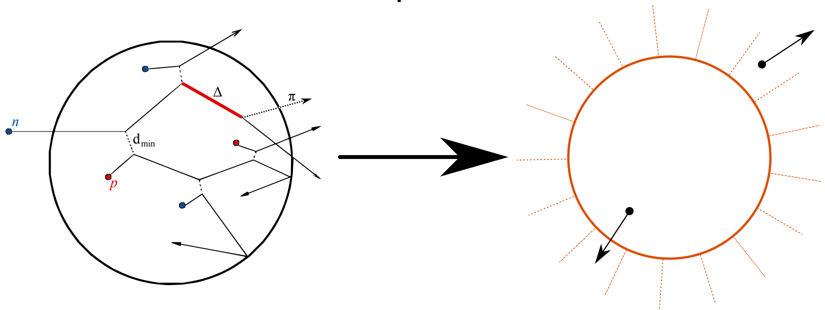
End of cascade

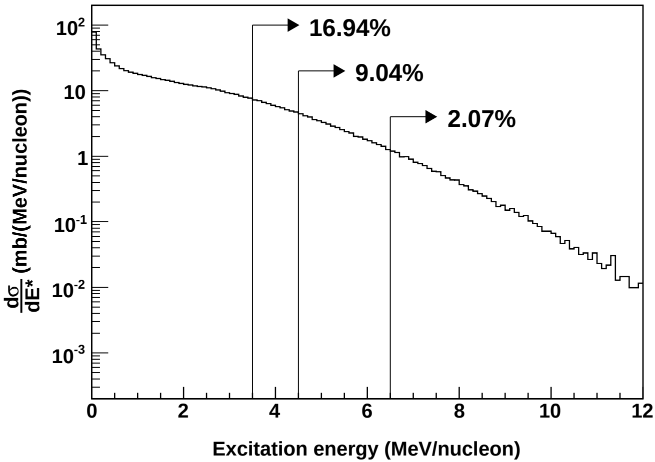
Two-step reaction



(JC after

End of cascade

p+^{56}Fe, 1 GeV



End of cascade

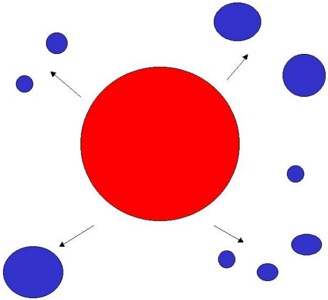
(JC after presenting
INCL4.5 results)

End of cascade

(JC after presenting INCL4.5 results)

Nuclear de-excitation

Multifragmentation



ID card

Simultaneous break-up

- Thermalised remnant
- Expansion
- Spinodal instabilities
- Liquid–gas phase transition?

The question

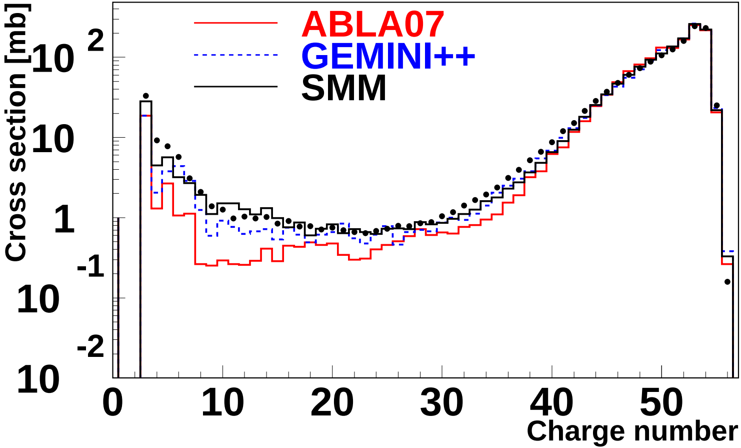
What is the signature of multifragmentation in a nucleon-nucleus reaction?

De-excitation models

	ABLA07	GEMINI++	SMM
multifragmentation	~yes	no	yes!
IMF emission	evaporation	asymmetric fission	evaporation

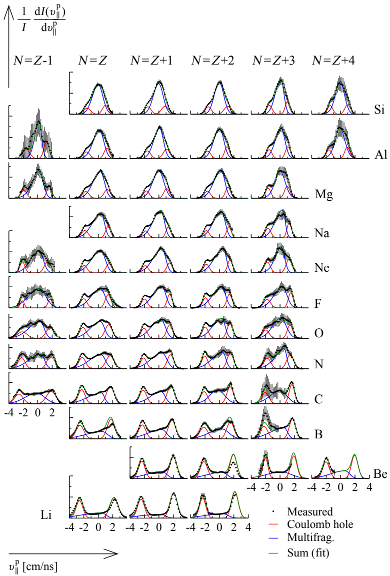
- ABLA07: Kelić *et al.*
  Report INDC(NDC)-0530 (2008) 181
- GEMINI++: Charity
  Report INDC(NDC)-0530 (2008) 139
- SMM: Bondorf *et al.*
  Phys. Rep. 257 (1995) 133

1-GeV p + ^{136}Xe



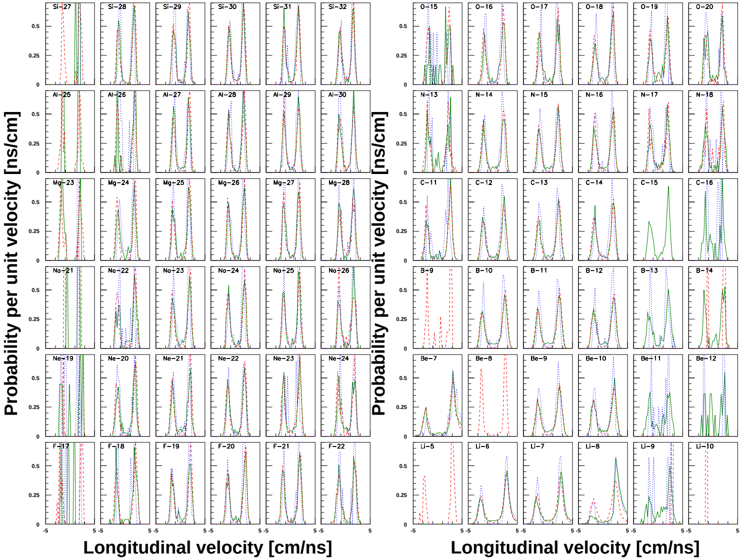
All models give ∼right inclusive cross sections

Longitudinal-velocity distributions



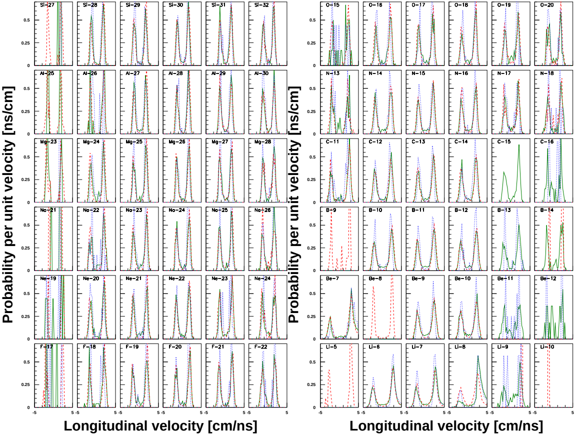
Napolitani *et al.*
arXiv:nucl-ex/0806.3372

Calculated longitudinal-velocity distributions



Calculated longitudinal-velocity distributions

Reproducing one-humped distributions is impossible

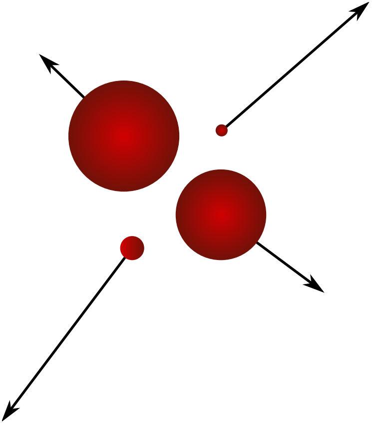


Calculated longitudinal-velocity distributions

One or two fragments much heavier than the rest

⇓

Coulomb-like kinematics



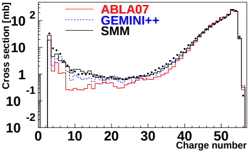
Plan

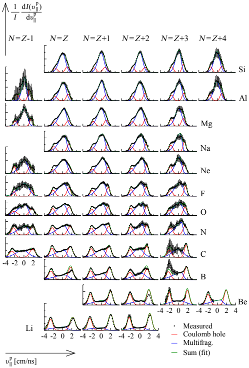
Conclusions

- Unanswered theoretical questions on the validity of cascade
- Extension to exotic nuclei
- Extension to nucleus-nucleus collisions

Conclusions

We can use INC models to study nuclear de-excitation!





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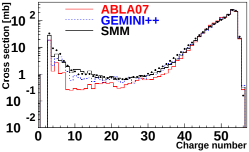
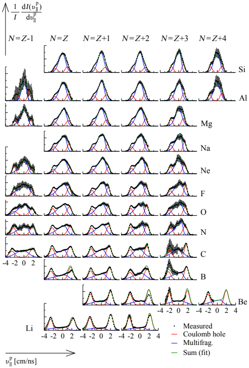
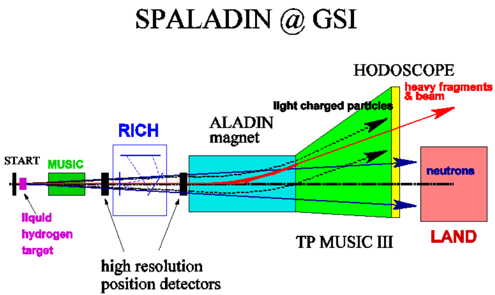




. . . and there is still some physics to understand

Plan

SPALADIN simulation

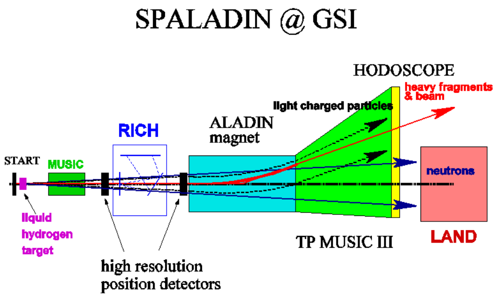


SPALADIN setup

- Inverse kinematics
- Simultaneous measurement of de-excitation products

E. Le Gentil *et al.*
Phys. Rev. Lett. 100 (2008) 022701

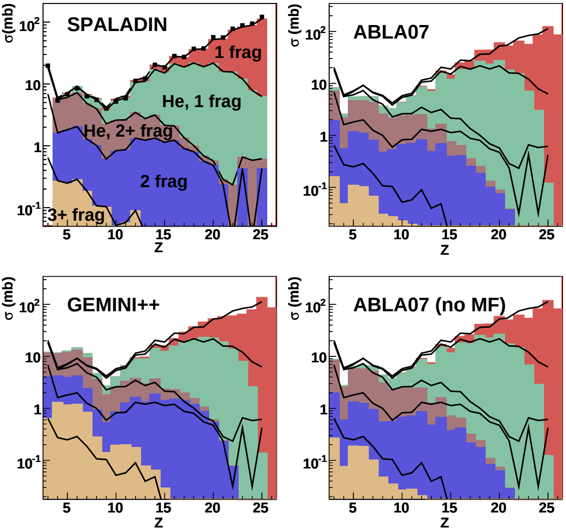
SPALADIN simulation



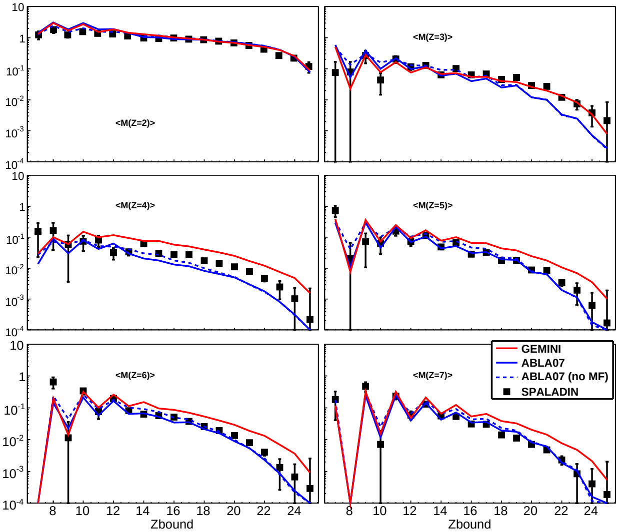
GEANT4 simulation

- Source = cascade+désexcitation events
- Filter the calculation with GEANT4 transport
- Thanks to T. Gorbinet and P. Kaitaniemi

Classification of SPALADIN events



Z_{bound} distributions



Z_1-Z_2 correlations