Test of the nuclear fragmentation models with Carbon fragmentation at 300 -950 MeV/n

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Introduction and motivation

Experiment FRAGM at ITEP TWAC

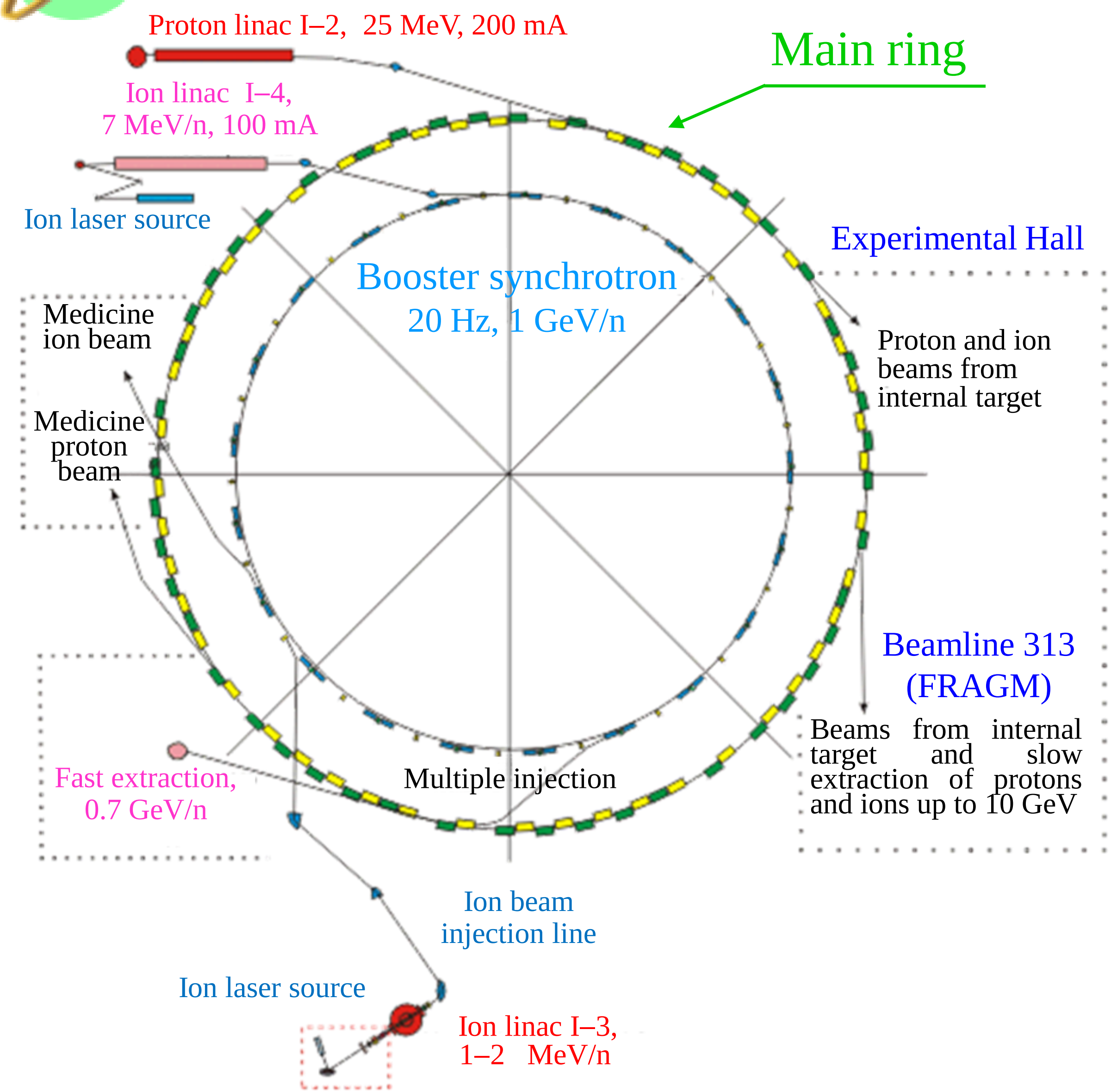
$^{12}C + A \rightarrow f + X$ (inverse kinematics)

fragments:	p, d, t, ^3He, ^4He, ^6He, ^6Li,…, ^{10}C, ^{11}C, ^{12}C
^{12}C kinetic energy:	0.3 – 3.2 GeV/nucleon on Be target
fragment angle:	3.5^o with respect to ^{12}C beam
different targets:	Be, Al, Cu, Ta for ^{12}C beam of 0.3 GeV/n
sensitivity:	up to 5 orders of the cross section magnitude

I will focus on the results of the runs at 0.3, 0.6 and 0.95 GeV/n

- good data for carbon fragmentation are needed for overall understanding of nucleus-nucleus collisions
- the carbon fragmentation in this energy region is also important for application in ion therapy where fragmentation is a main source of irradiation behind the Bragg peak
- few ion-ion interaction models exist that aim at precise description of fragmentation processes. They have to be tested at different processes and at wide kinematical region.

TWAC – ITEP



TWAC – TeraWatt Accumulator Complex

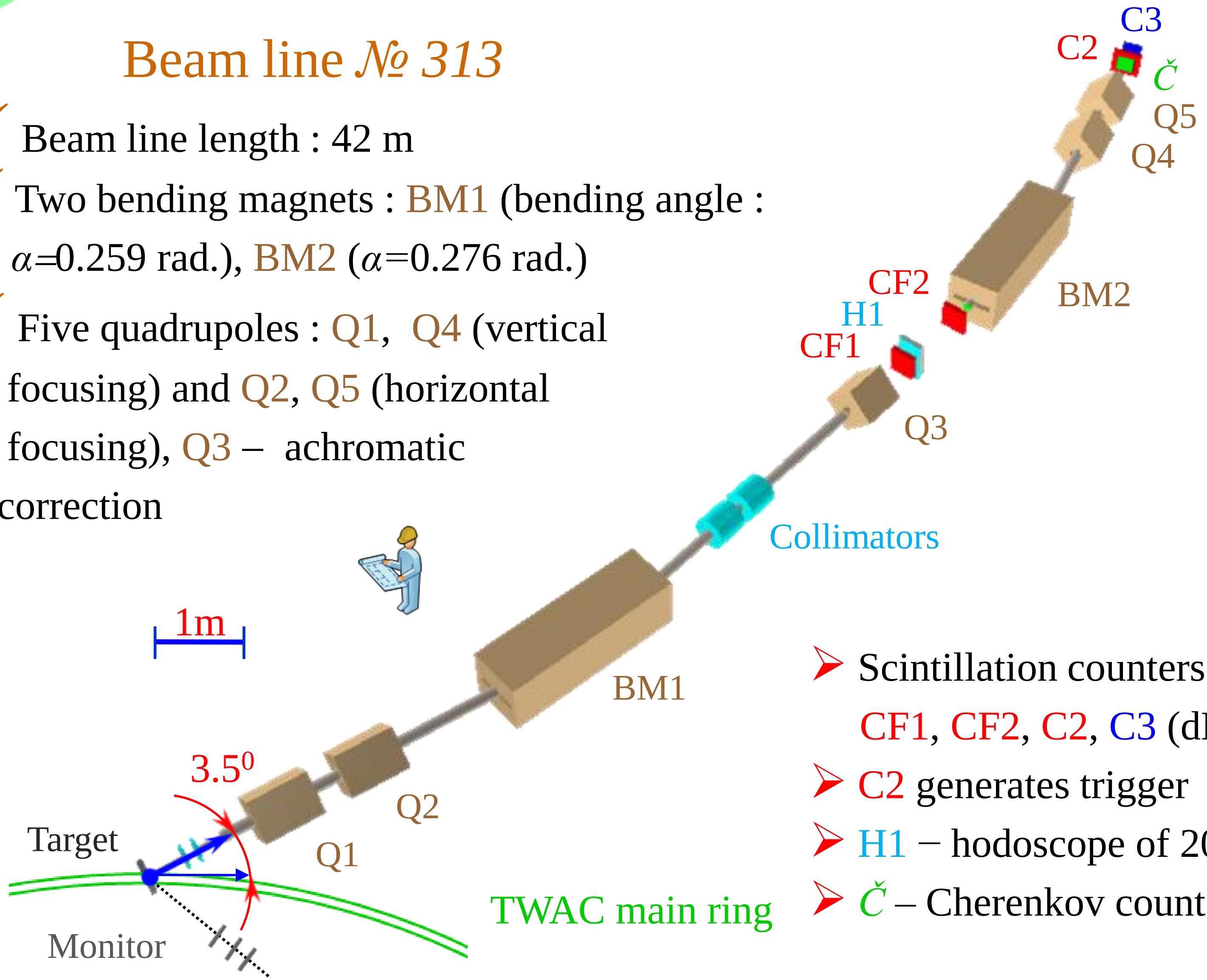
TWAC last parameters

- ✓ Proton acceleration :
  50 – 10000 MeV
- ✓ Ion acceleration :
  up to 4 GeV/nucleon
- ✓ Ion accumulation :
  up to 700 MeV/nucleon
- ✓ Accelerating ions :
  up to ^{56}Fe
- ✓ As a result of the strong fire accident in 2012, TWAC was decommissioned. The restoration / modernization of the accelerating–storage complex is a priority task of ITEP

Experiment FRAGM

Beam line *№ 313*

- ✓ Beam line length : 42 m
- ✓ Two bending magnets : BM1 (bending angle : α=0.259 rad.), BM2 (α=0.276 rad.)
- ✓ Five quadrupoles : Q1, Q4 (vertical focusing) and Q2, Q5 (horizontal focusing), Q3 – achromatic correction

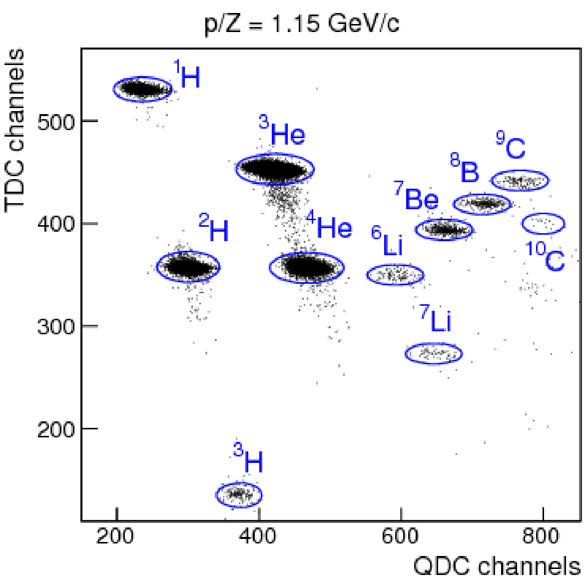


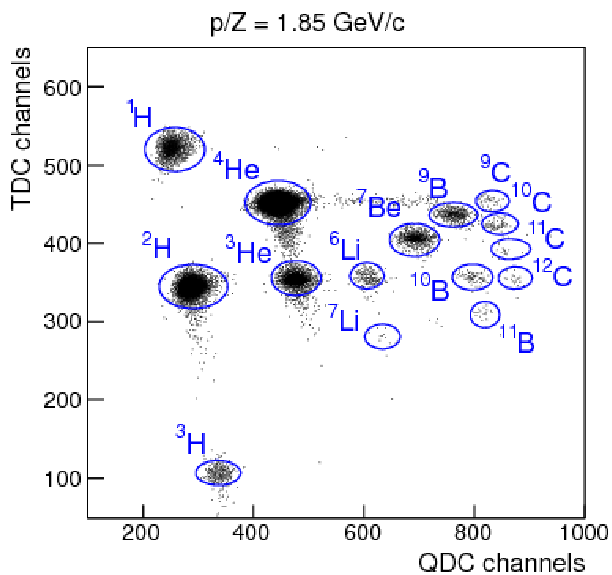
- Scintillation counters : CF1, CF2, C2, C3 (dE/dx, TOF)
- C2 generates trigger
- H1 – hodoscope of 20 elements
- Č – Cherenkov counter

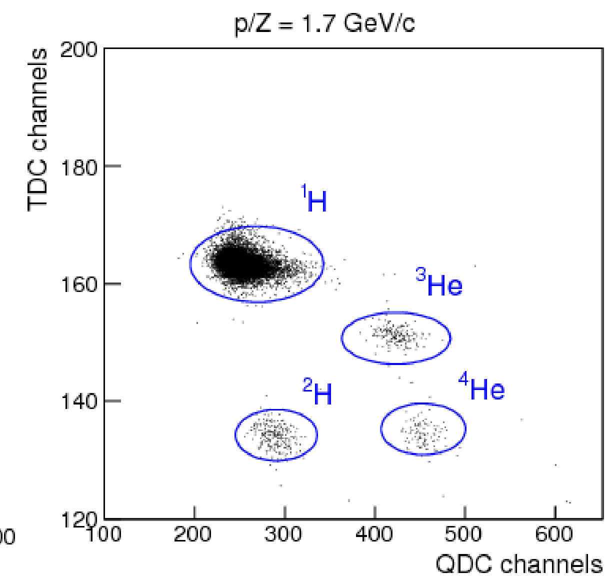
Fragment separation in FRAGM

C – Be collisions at different T_0

T_0 = 0.3 GeV/nucleon | T_0 = 0.6 GeV/nucleon | T_0 = 0.95 GeV/nucleon



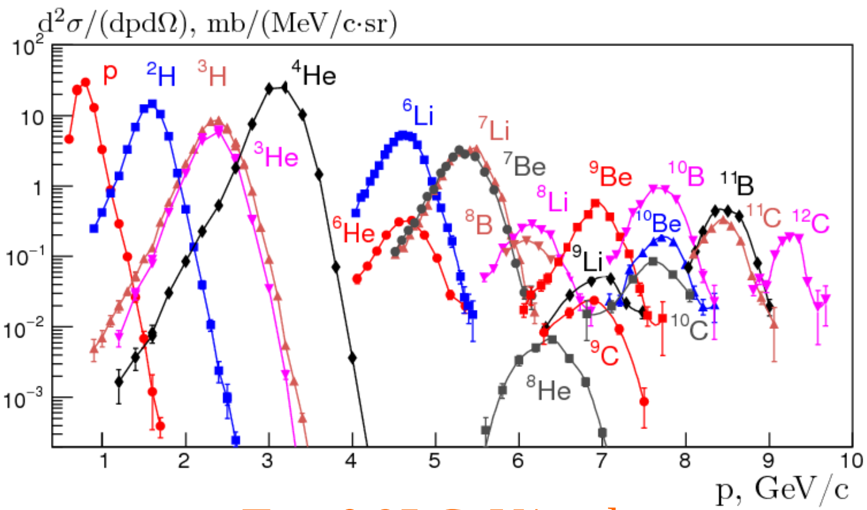




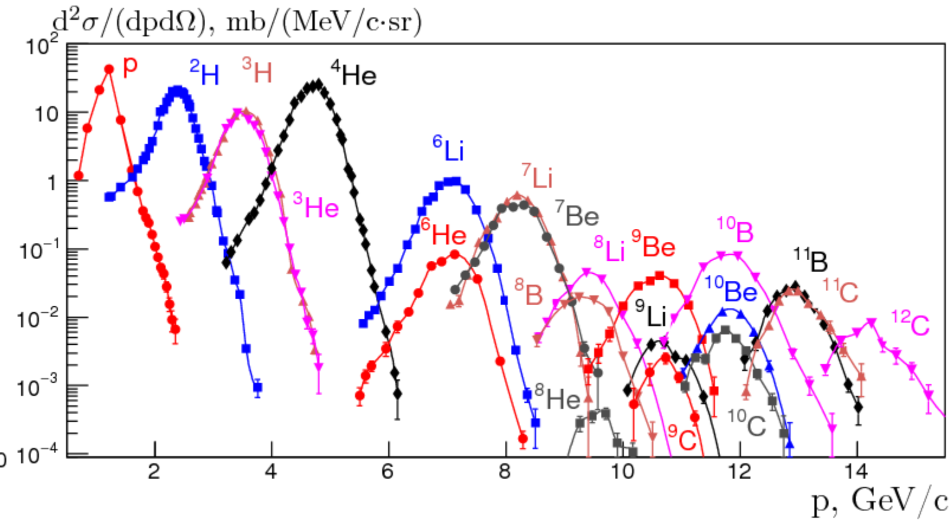
- ✓ QDC (from CF1) vs TDC between CF1 and C2
- ✓ Regions of the different fragments are well separated and can be clearly selected

Measured spectra of the fragments

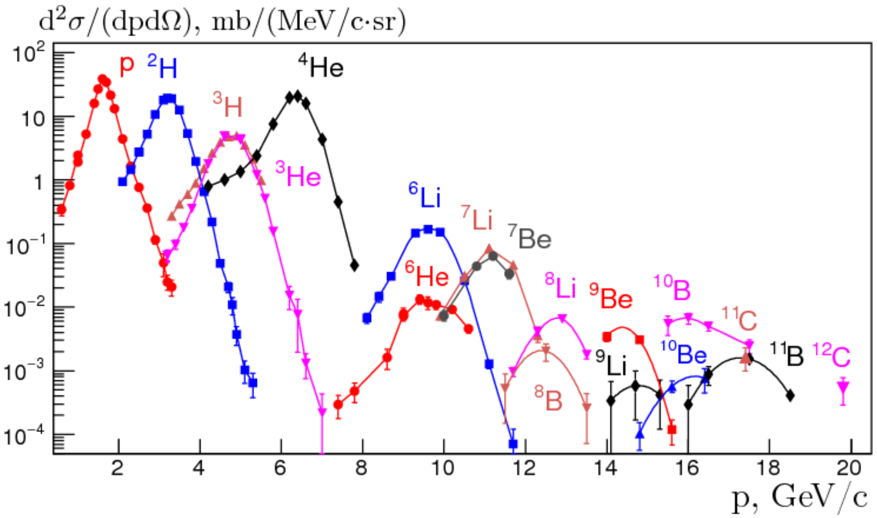
T_0 = 0.3 GeV/nucleon



T_0 = 0.6 GeV/nucleon



T_0 = 0.95 GeV/nucleon



- ✓ Measured up to 21 fragments from proton to ^{12}C (at T_0 = 0.95 GeV/nucl. only 18)
- ✓ Differential cross sections for protons at all energies have been included in the Experimental Nuclear Reaction Data (EXFOR).

Ion – ion interaction models

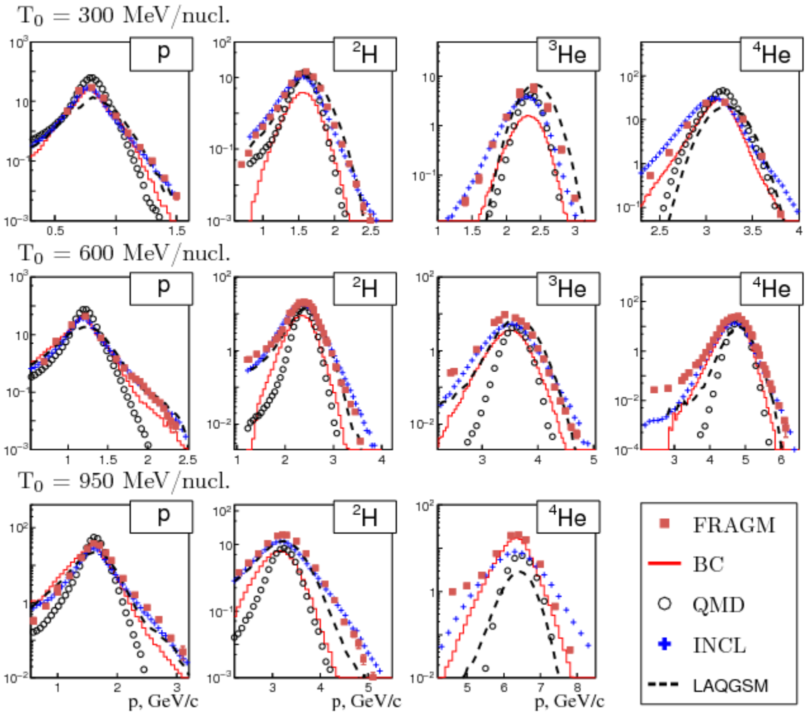
- Binary Cascade (BC, GEANT4 toolkit, G. Folger *et al.*, EPJA 21 (2004) 407) :
  - Either projectile or target has to be ^{12}C or lighter
  - Original approach to intra-nuclear cascade
- Quantum Molecular Dynamics (QMD, GEANT4 toolkit)

  T. Koi *et al.*, AIP Conf. Proc. 896 (2007) 21:
  - Can be used with light and heavy ions
  - All nucleons are considered as participants and they are propagated in phenomenological potential
- Liege Intranuclear Cascade (INCL++, J. Dudouet *et al.*, PR **C**89 (2014) 054616) :
  - Model is alive, often modified, in the GEANT4, projectiles lighter than A = 18?
  - Combines best features of the BC and QMD
- Los Alamos version of Quark Gluon String Model (LAQGSM03.03)

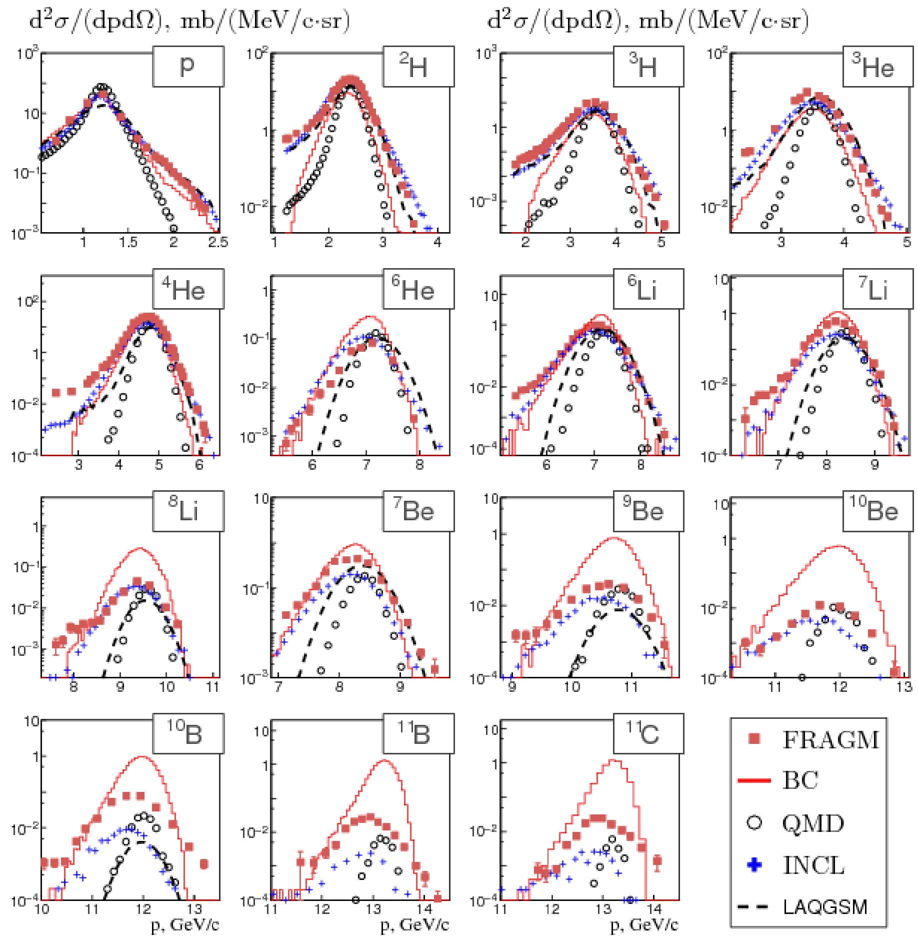
  LA-UR-11-01887, experts S. Mashnik and K. Gudima
  - First stage is the intranuclear time-dependent cascade developed at JINR
  - Can be used in a wide energy range up to 1 TeV/nucleon for all ions

Comparison : FRAGM data vs models

Differential cross sections at T_0 = 0.3 / 0.6 / 0.95 GeV/nucleon



Differential cross sections for fragments un to ^{11}C at T_0 = 0.6



- INCL++ predictions give better description of FRAGM data
- INCL++ predicts the cross section normalization better than other models

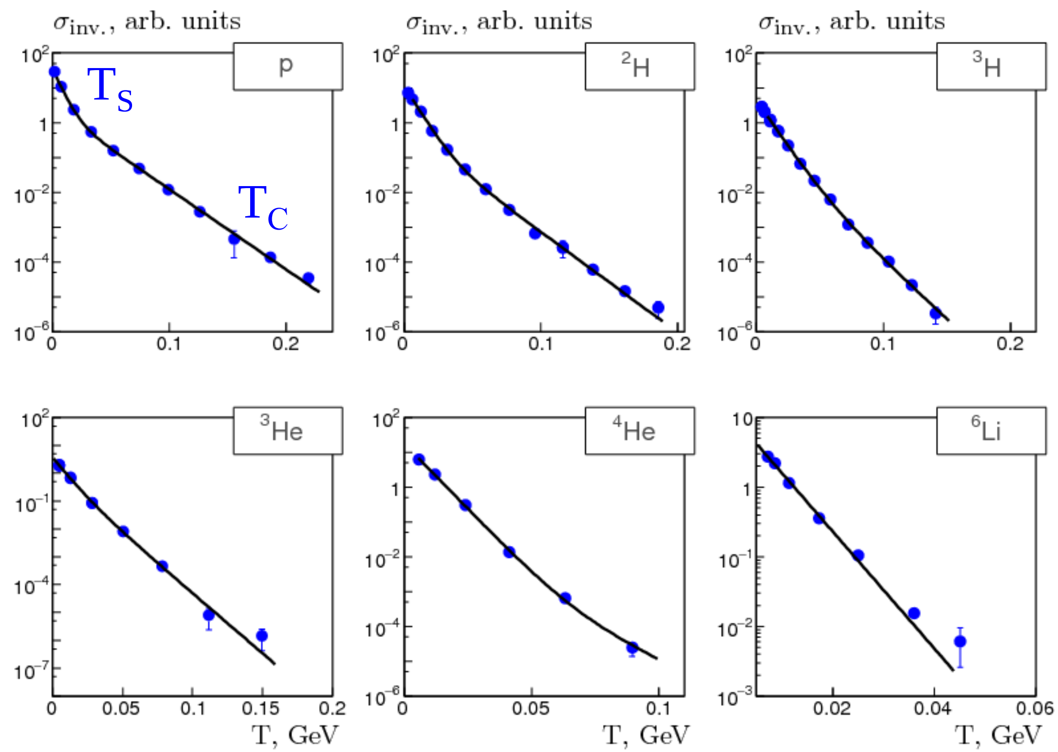
LF kin. energy spectra in projectile rest frame

- In the projectile rest-frame the kinetic energy spectra (*T*) can be described by a sum of two exponents with slope parameters T_S (evaporation region) and T_C (high momentum or cumulative tail) in the form :

$$Ed^3\sigma/d^3p = A_S e^{(-T/T_S)} + A_C e^{(-T/T_C)}$$

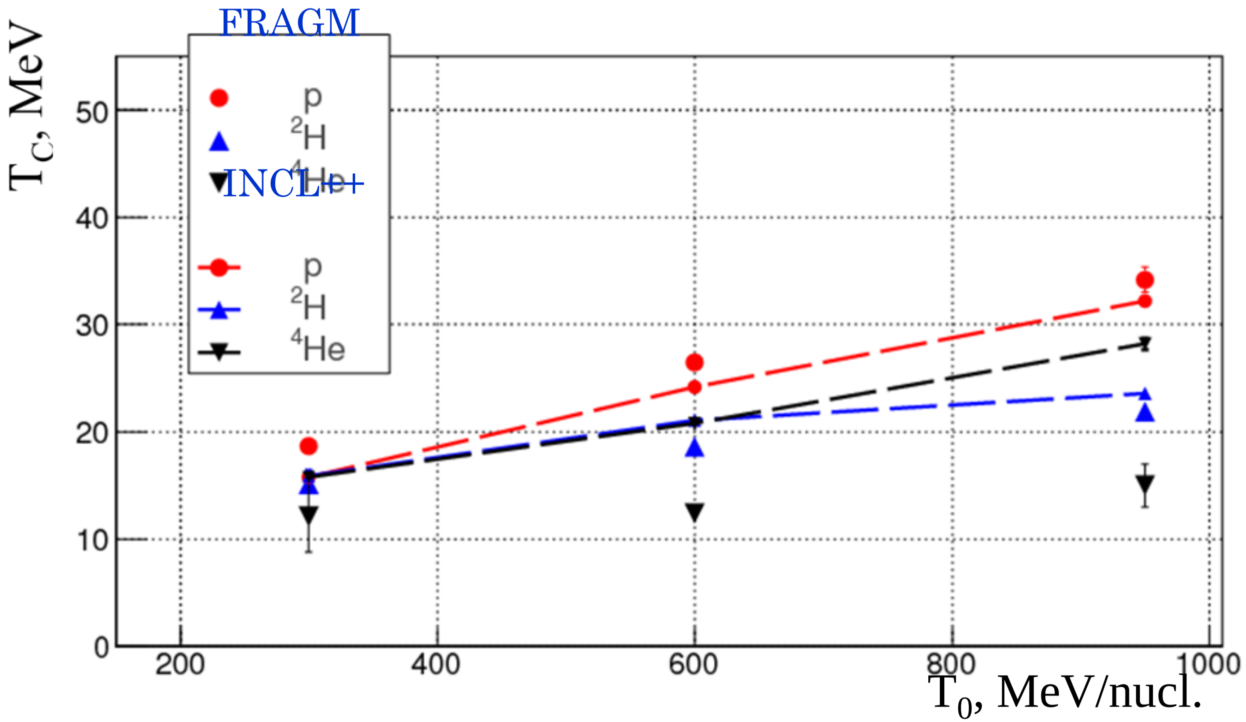
T_0 = 600 MeV/nucl.

- Two components are clearly seen by eye for p and d, can be found by fit for t,He-3,He-4 and absent for Li-6.
- It is not in agreement with thermodynamic models and thermodynamic equilibrium,



Cumulative parameter T_C

- ✓ Slope T_C rises with increase of projectile kinetic energy. For pA it is 50 MeV at high energy.
- ✓ Slope T_C decreases with fragment atomic number.
- ✓ Model INCL++ predicts rather well energy dependence for T_C for protons and deuterons, but fails to do it for ^4He.



Comparison : parameter T_C vs energy and A

Fragment	T_C (MeV) , experiment FRAGM			T_C [*]
	(T_0 = 300 MeV)	(T_0 = 600 MeV)	(T_0 = 950 MeV)	
p	18.7±0.4	26.5±0.6	34.3±1.2	25.5±1.0
^{2}H	15.1±0.7	16.8±0.4	21.9±1.9	16.0±1.0
^{3}H	12.5±0.9	16.6±0.6	-------	15.0±1.0
^{3}He	10.1±0.6	16.8±2.2	25.4±12.2	19.0±1.0
^{4}He	12.1±0.3	12.4±0.6	15.0±0.2	14.0±1.0

T_C[*] T. Odeh et al., PRL 84 (2000) 4557, ^{197}Au – ^{197}Au collisions at 1 GeV/nucl.

- T_C decreases smoothly as the fragment atomic number grows and rises with energy

Conclusions

✓ Fragment yields in the reaction $^{12}C + Be \rightarrow f + X$ were measured at ion incident energies 0.3, 0.6, 0.95 GeV/nucleon in the FRAGM experiment at TWAC at ITEP

✓ Differential cross sections for a wide range of fragments were obtained

✓ Fragment momentum spectra were compared with the predictions of four ion–ion interaction models: INCL++, LAQGSM03.03, QMD and BC

✓ Fragment kinetic energies spectra in the rest frame of the projectile for light fragments can be fitted with the sum of two exponent with different slope parameters

Thank You

Coalescence model

- In the coalescence model, yield of the fragments is determined by composition of the invariant nucleon distribution with empirical coefficient C_A in the form:

$$(1/p_A)(d^2\sigma/dT_A d\Omega) = C_A(1/p_p\, d^2\sigma/dT_p)^A$$

$T_A = AT_p$, $p_A = Ap_p$, C_A – coalescence coefficient, A – fragment mass number

- "Radius" of the source in momentum space p_0 can be calculated from C_A:

$$p_0{}^3 = 3m_{nucl}\, \sigma_{tot}\, x!y!((Z_{proj}+Z_{targ})/(N_{proj}+N_{targ}))^y (x + y)^2\, C_A{}^{1/(x+y-1)}$$

Z, N – proton and neutron numbers, $x + y = A$ (proton and neutron numbers for fragment)

σ_{tot} – total cross section for C – Be collision :

σ_{tot} = 772.8 mb (T_0 = 0.3 GeV), σ_{tot} = 823.8 mb (T_0 = 0.6 GeV), σ_{tot} = 856.7 mb (T_0 = 0.95 GeV)

- Space radius of the source R is given by the formula:

$$V = 4/3\, \pi R^3 = (x!y!)^{1/(x+y-1)} (3h/4\pi\, \tilde{p}_0{}^3)$$

Coalescence parameters

Energy, MeV/nucl.	σ0, mb	Fragment	C_A, [mb/sr(GeV)^2]$^{1-A}$	$\tilde{p}_0$, MeV/c	R, fm
300	772.86	^{2}H	$(1.73 \pm 0.41)\times10^{-5}$	122 ± 10	3.9 ± 0.3
		^{3}H, ^{3}He	$(6.30 \pm 0.85)\times10^{-10}$	186 ± 4	2.9 ± 0.1
		^{4}He	$(6.93 \pm 1.44)\times10^{-15}$	198 ± 5	2.8 ± 0.1
600	823.8	^{2}H	$(3.47 \pm 0.25)\times10^{-5}$	157 ± 4	3.0 ± 0.1
		^{3}H, ^{3}He	$(5.51 \pm 0.73)\times10^{-10}$	186 ± 4	2.9 ± 0.1
		^{4}He	$(6.46 \pm 1.29)\times10^{-15}$	201 ± 4	2.8 ± 0.1
950	856.73	^{2}H	$(1.02 \pm 0.10)\times10^{-5}$	106 ± 4	4.5 ± 0.2
		^{3}H, ^{3}He	$(1.87 \pm 0.11)\times10^{-10}$	157 ± 1	3.4 ± 0.1
		^{4}He	$(2.89 \pm 0.37)\times10^{-15}$	186 ± 3	3.0 ± 0.1

$R(^{12}C(g.s.)) = 2.5\,\mathrm{Fm}$, $R(^{12}C(7.6\ 5\,\mathrm{MeV})) = 2.9\,\mathrm{Fm}$