Neutron Emission and Evolution of Hot Nuclei Formed in High-Energy Reactions

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- Space-time picture of particle emission
- Recent experiments and Neutron data
- Reaction kinematics and Moving Source Model
- Results of MSM analysis
  - Source characteristics
  - Source origin
  - Source contributions to neutron yield
- Conclusion

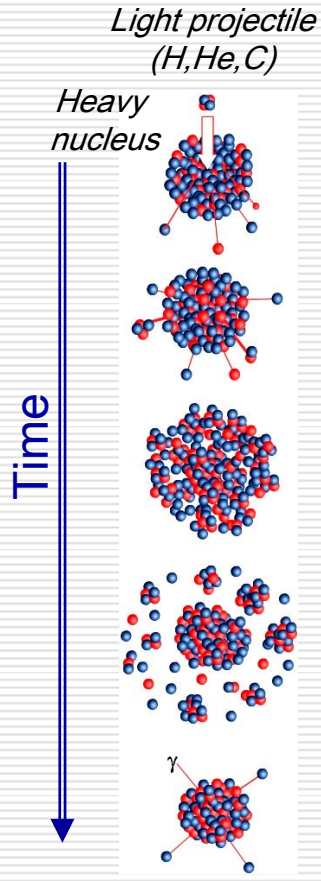
Space-time picture of particle emission

Collisions of GeV hadrons and light nuclei with heavy nuclei
are effective method of
hot nuclear system production with small excitation of collective modes

Probability of hot nuclear system production in reactions:

π, p + A	1-12 GeV	*Shibata et al. 1983 (Exp.)*	**~30%**
p + Au	2.55 GeV	*Avdeychikov et al. 1987 (Exp.,The.)*	**~20%**
p + Au	2 GeV	*Ledoux et al. 1998 (Exp.,The.)*	**~25%**
p + Au	2.16 GeV	*Avdeyev et al. 2002 (Exp.,The.)*	**~20%**
^{4}He + Au	4, 14.6 GeV	*Avdeyev et al. 2002 (Exp.,The.)*	**~25-30%**
C + Au	22.4 GeV		

Space-time picture of particle emission



First collisions of projectile and target nucleons
Source 1 (CC&PC)

Hot non-equilibrium stage
Source 2 (CC)

Stage of expansion and thermalization

Freeze-out stage (fragmentation)
Source 3 (CC)

De-excitation of fragments by evaporation
Source 4 (CC&PC)

Emitted particles

n, *p*, π

n and LCP

n, LCP and IMF

n

CC – Central collisions, PC – Peripheral Collisions

Recent experiments & Neutron data

Collisions of relativistic light nuclei with nuclei

Neutron emission (TOF data)

1-9 GeV p+A (ITEP, 1983)

0.1-0.8 GeV p+A (LANL, 1989-1993)

0.8-3 GeV p+A (KEK, 1995)

0.8-1.6 GeV p+A (Saclay, 2002)

0.8-1.6 GeV p+A (ITEP, 2003)

2 GeV p+A (JINR/RI, 2006-2008)

2 GeV d+Pb
4 GeV ^{4}He+Pb } (JINR/RI, 2006)
24 GeV C+Pb

Charged particle emission

1-19 GeV p+Xe (AGS, 1989)

1 AGeV Au+C (EOS, 1998)

2 GeV p,^{3}He+Ag-U (Saclay, 1998)

2-8 GeV p+Au
4,14.6 GeV ^{4}He+Au } (FASA, 1999-2002)
22.4 GeV C+Au

1 GeV p+A (PINP, 2001)

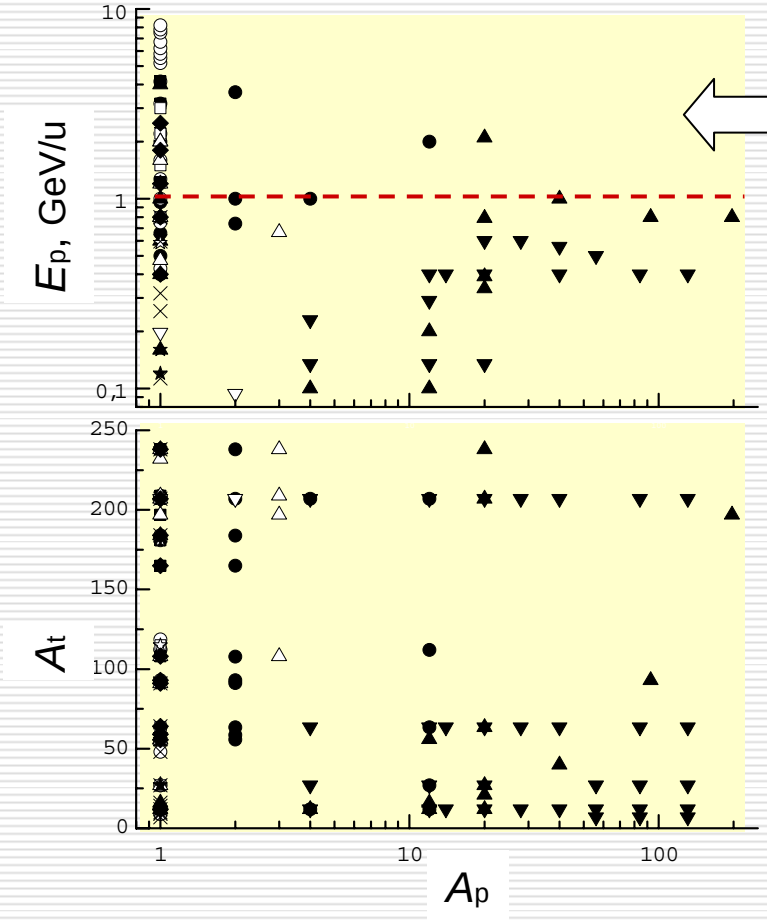
1.8-4.8 GeV ^{3}He+Ag,Au (ISiS, 2004)

2.5 GeV p+Au (PISA, 2004)

0.2-1.4 GeV p+Xe (CHICSi, 2007)

Recent experiments & Neutron data

Experiments on neutron production

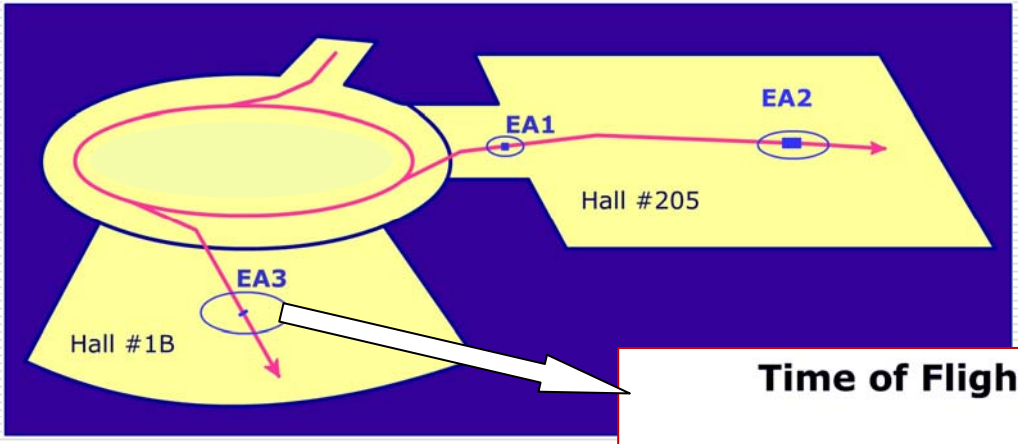


Neutron data set is very poor and there is only a few experiments with GeV nuclear beams !

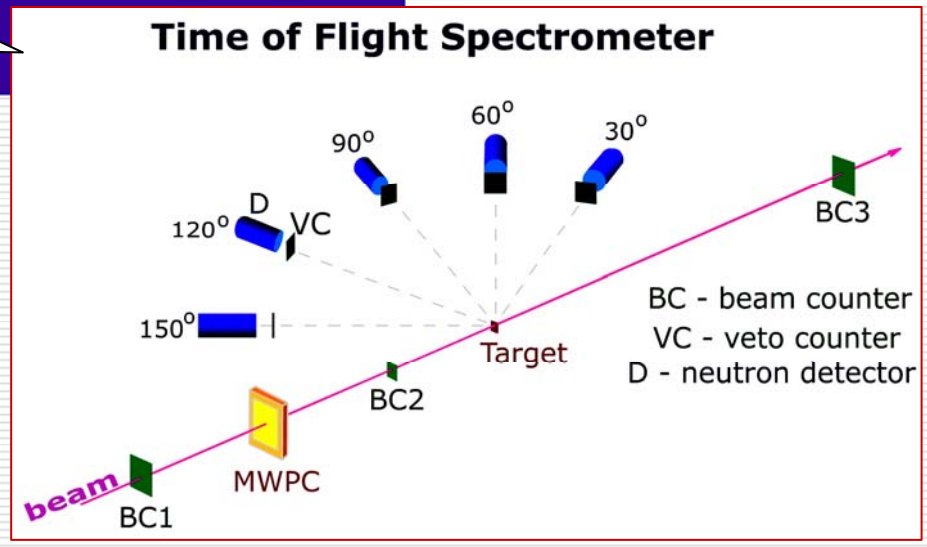
● - JINR , ○ - ITEP, ■ - PS CERN, □ - PS KEK,
▲ - BEVALAC, △ - SATURNE,
▼ - HIMAC, ▽ - GANIL, ☆ - PSI,
◆ - COSY, ✕ - LAMPF, ★ - IUCF.

Recent experiments & Neutron data

Measurements in Dubna (JINR/RI collaboration)



Accelerator complex of
Laboratory of High Energy Physics
JINR



Recent experiments & Neutron data

Measurements in Dubna (JINR/RI collaboration)

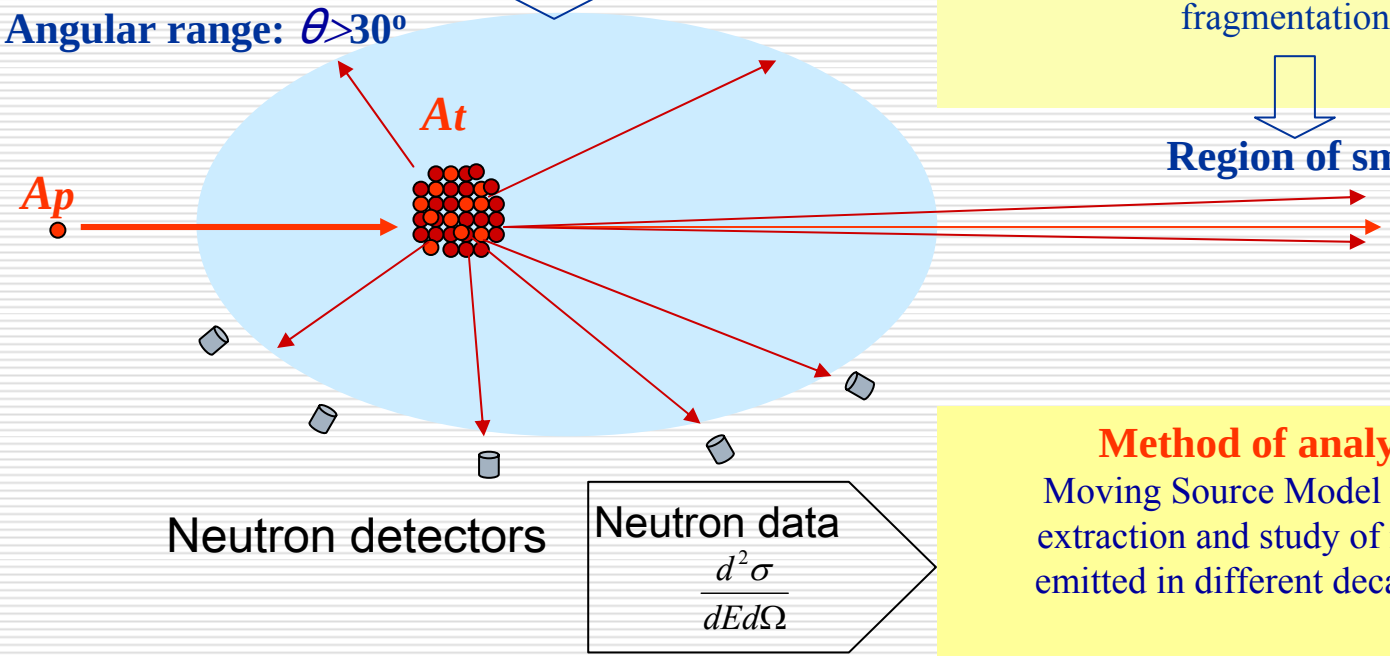
Studied process:

Neutron emission in decay of excited nuclear system

Not studied process:

Neutron production in elastic and quasi-elastic interactions and projectile fragmentation

Region of small angles



Method of analysis:

Moving Source Model used for extraction and study of neutrons emitted in different decay stages

Recent experiments & Neutron data

Measurements in Dubna (JINR/RI collaboration)

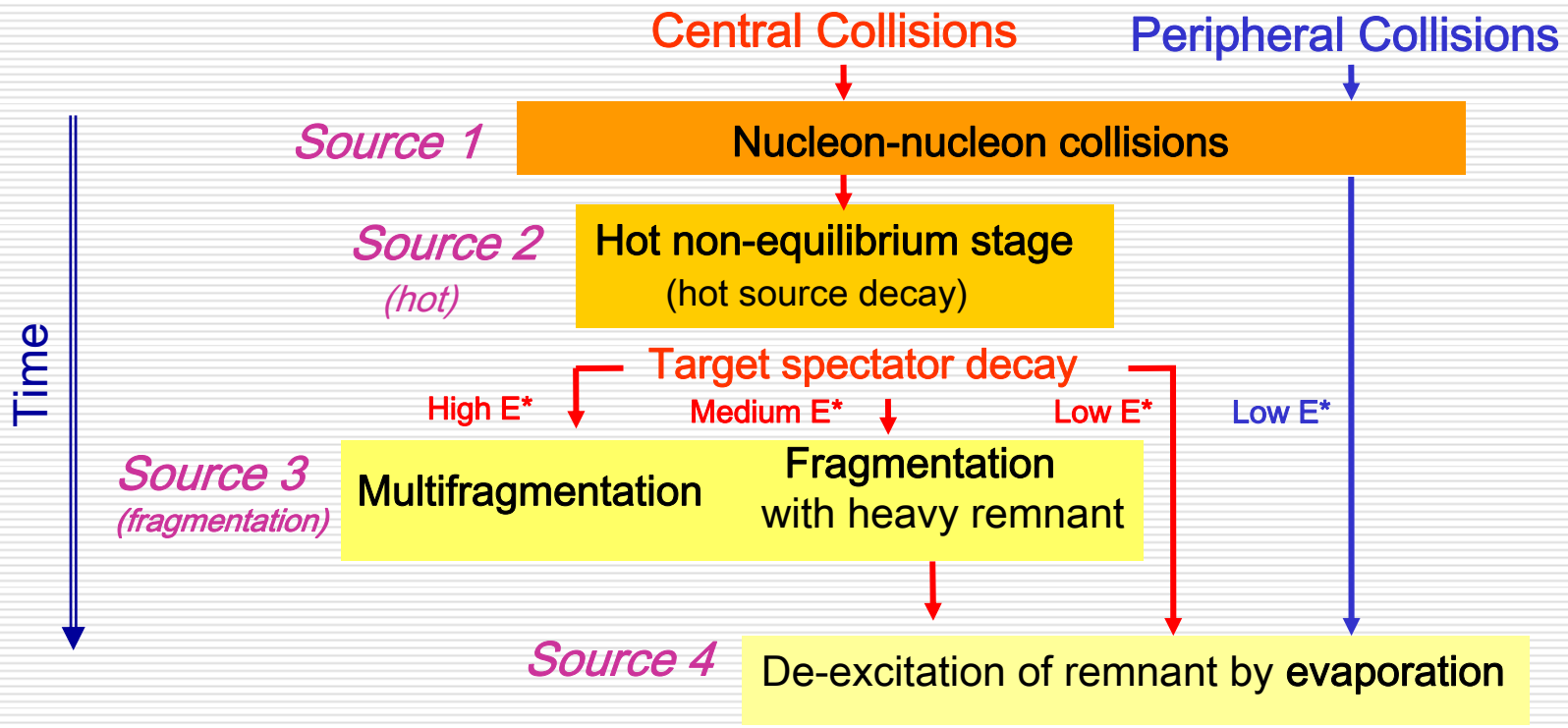
List of measurements

Projectile	Energy	Targets
p	2 GeV	Be, Al, Cu, Cd, Pb
d	2 GeV	Pb
He-4	4 GeV	C, Pb
C-12	24 GeV	C, Al, Cu, Cd, Pb

Status of data analysis: – finished

– in progress

Reaction kinematics and Moving Source Model



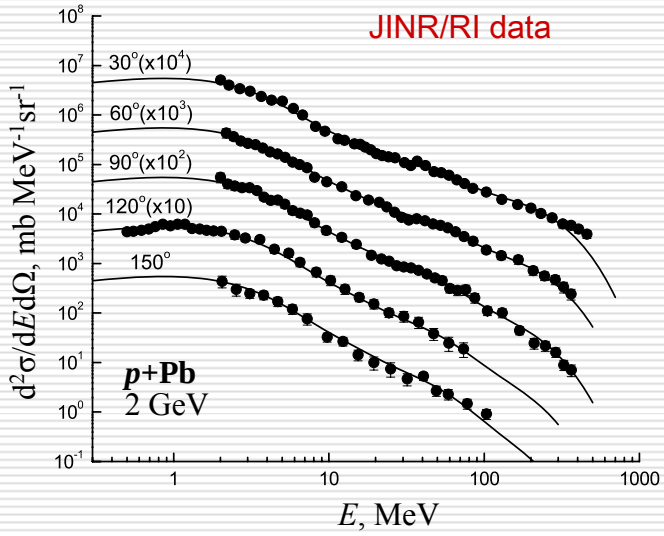
Reaction kinematics and Moving Source Model

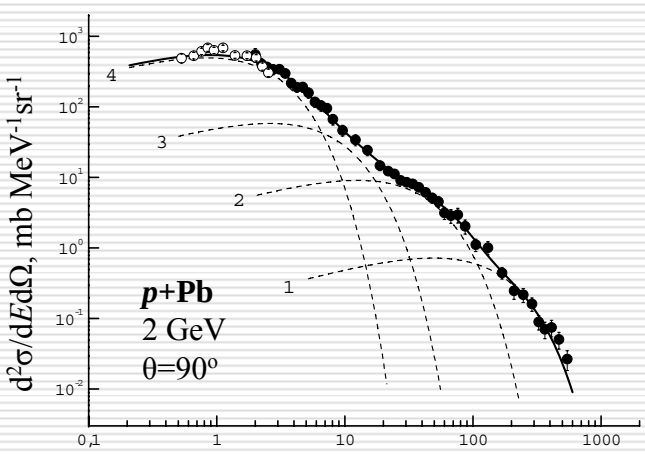
$$\frac{d^2\sigma}{dEd\Omega} = \sum_{i=1}^{4} pA_i \exp\left(-\left(\frac{E + m - p\beta_i \cos\theta}{(1-\beta_i^{\,2})^{1/2}} - m\right)/T_i\right)$$

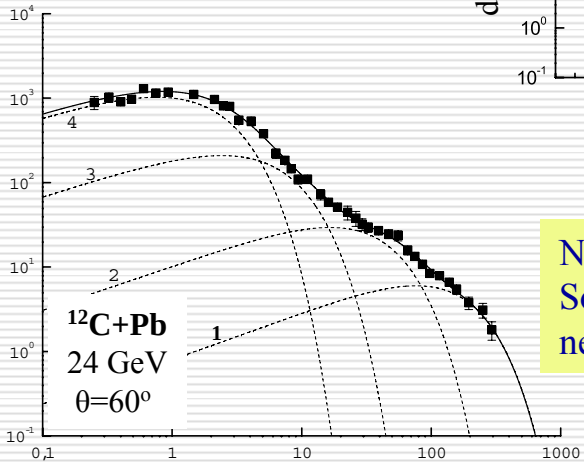
Parameters:

A_i – amplitude
β_i – velocity
T_i – temperature

$\beta_1 > \beta_2 > \beta_3 > \beta_4$
$T_1 > T_2 > T_3 > T_4$





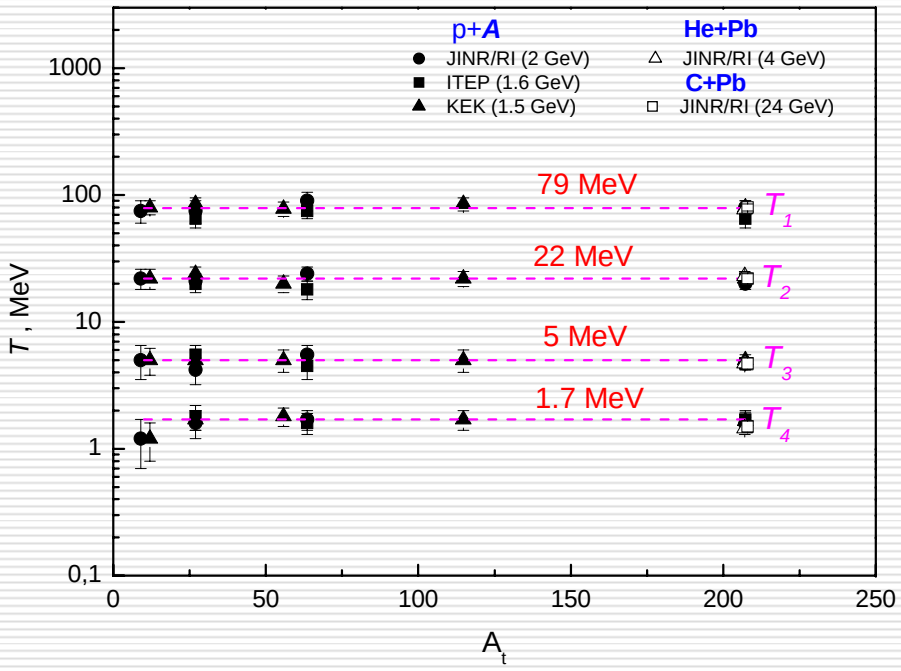


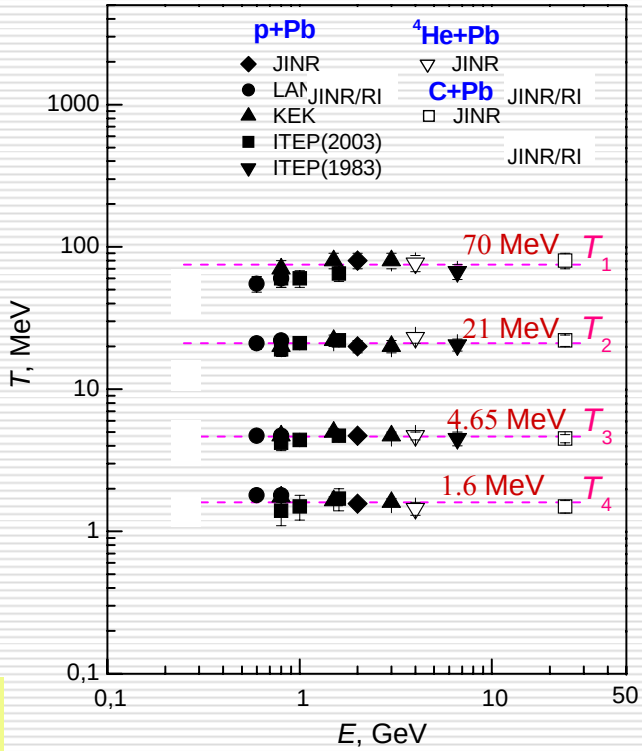
Neutrons from Hot and Fragmentation Sources dominate in middle part of neutron energy spectra !

Results of MSM analysis

Source characteristics

Temperatures



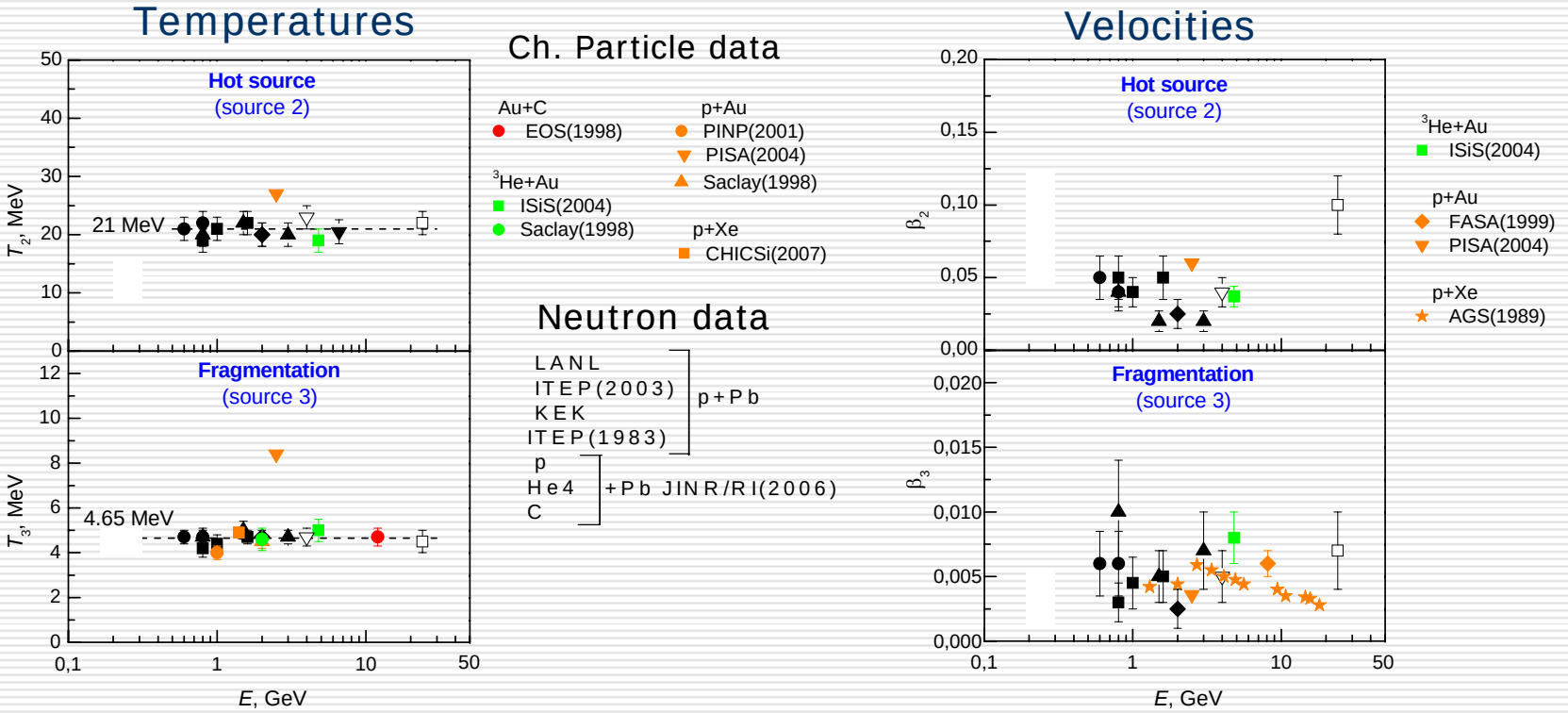


Constant values of source temperatures, independent of target, projectile and energy are observed !

Results of MSM analysis

Source characteristics

Hot & Fragmentation Sources



Neutron and LCP sources have the same origin,
or these particles are emitted in the same decay processes !

Results of MSM analysis

Fragmentation Source

Nuclear Thermometers

- Double ratios of isotopic yields (ALADIN, EOS, INDRA, ISiS, CHICSi and PNPI)
- Slopes of kinetic-energy spectra
  - LCP (AGS,Saclay, PISA)
  - Thermal bremsstrahlung photons (TAPS)
  - **Neutrons (Dubna)**
- Isospin thermometer (FRS)

Freeze-out temperature $<T_f>$

Neutron thermometer is unique tool for determination of hot nucleus temperature !

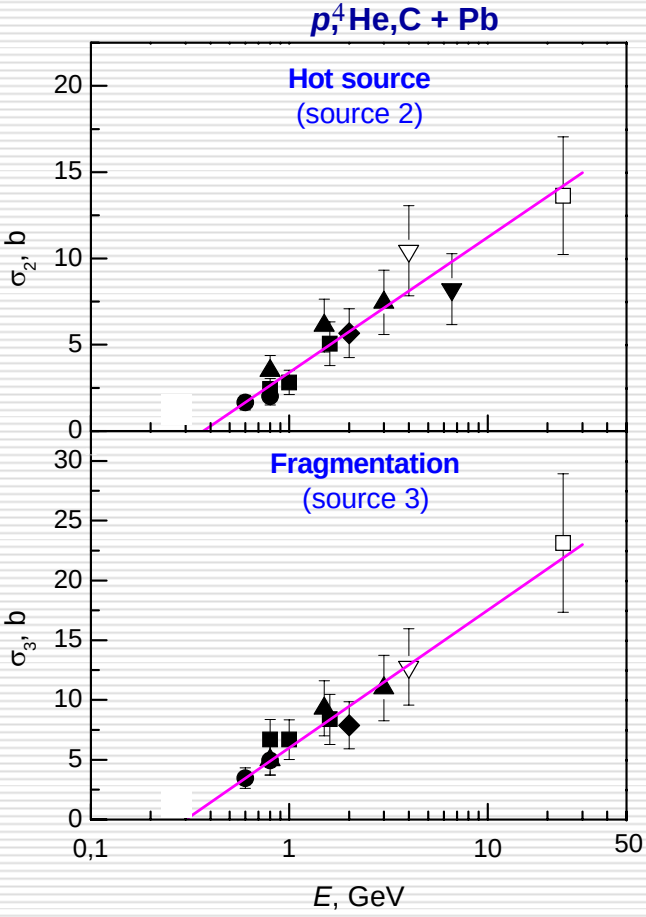
Recent results

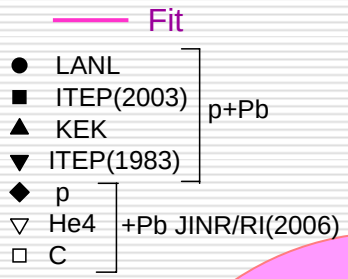
Neutron thermometer	**4.65(0.15) MeV**
Double ratios of isotopic yields	
EOS (DT-He)	4.7(0.4) MeV
ISiS (DT-He)	5.0(0.5) MeV
CHICSi (Li-He)	4.9(0.2) MeV
Slope of LCP energy spectra	
Saclay (Z=2)	4.5(0.3) MeV

Results of MSM analysis

Source origin

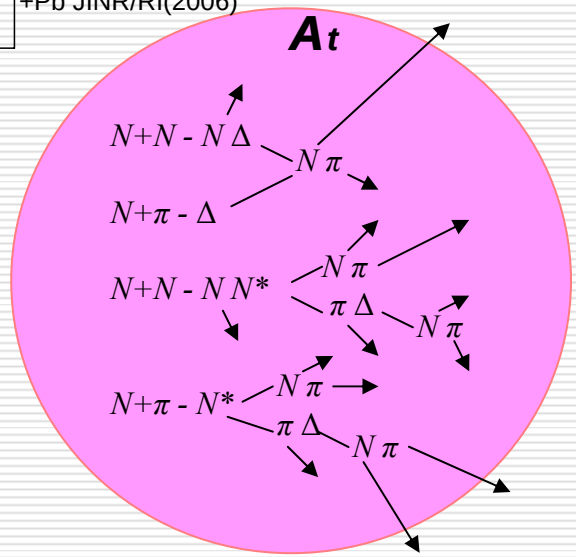
Hot & Fragmentation Sources

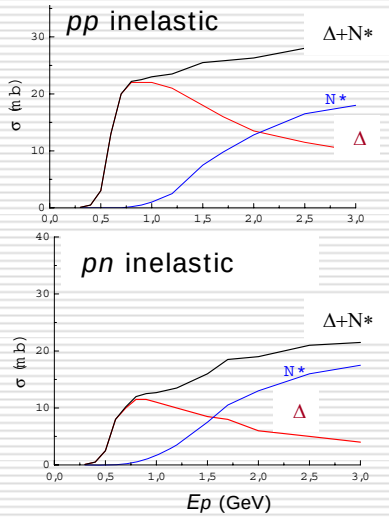




Source of particles & heating

Beam energy ⇨ Δ, N^*, π production ⇨ Target heating





$\beta_2 \sim 0.02$ & $t_2 \sim 25$ fm/c → $L(S_2) < 1$fm

Results of MSM analysis

Source contributions to neutron yield

Mean neutron multiplicity of *Source Si* $M_i = \dfrac{\sigma_i}{\sigma_{in}}$

Total mean neutron multiplicity $M_n = \sum_{i=1}^{4} M_i = \dfrac{\sigma_n}{\sigma_{in}}$

For ***pA*-reactions at 1.5-2 GeV**

A_t-dependence from MSM analysis:

$$M_1 = 0.3A_t^{1/3}$$

$$M_2 = 0.2 + 0.0143A_t$$

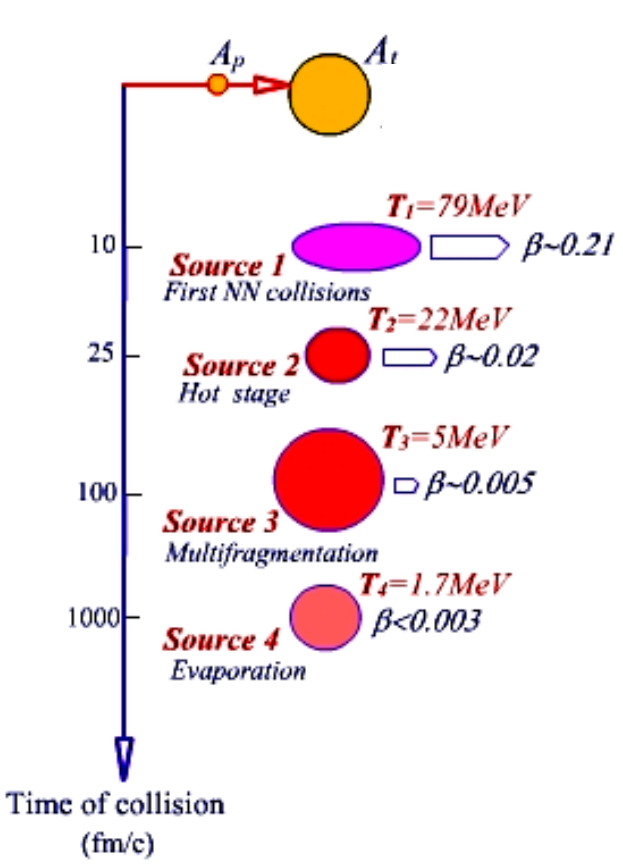
$$M_3 = 0.022A_t$$

$$M_4 = 0.008A_t^{4/3}$$

$$M_n = 0.2 + 0.3A_t^{1/3} + 0.0363A_t + 0.008A_t^{4/3} \quad \text{or} \quad M_n \approx 0.2 + 0.092A_t$$

Results of MSM analysis

Source characteristics



p(1.8 GeV)+A

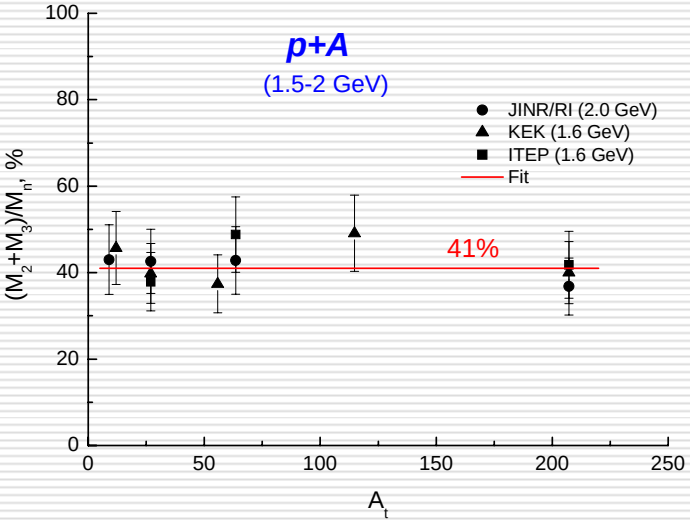
	Source Contribution to Neutron Yield		
	Al	Cu	Pb
M_1	0.9	1.2	1.8
M_2	0.6	1.1	3.2
M_3	0.6	1.4	4.6
M_4	0.65	2	9.8
M_n	2.75	5.7	19.4

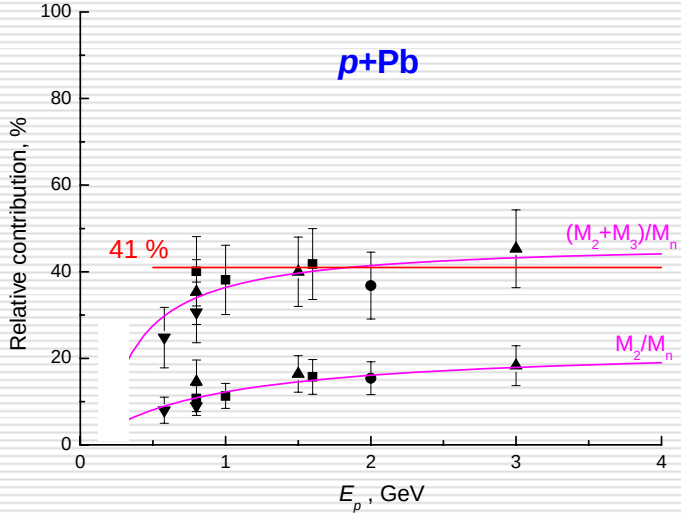
Hot and Fragmentation Sources give large fraction of emitted neutrons in high-energy reactions !

Results of MSM analysis

Source contributions to neutron yield

Hot & Fragmentation Sources





JINR/RI data

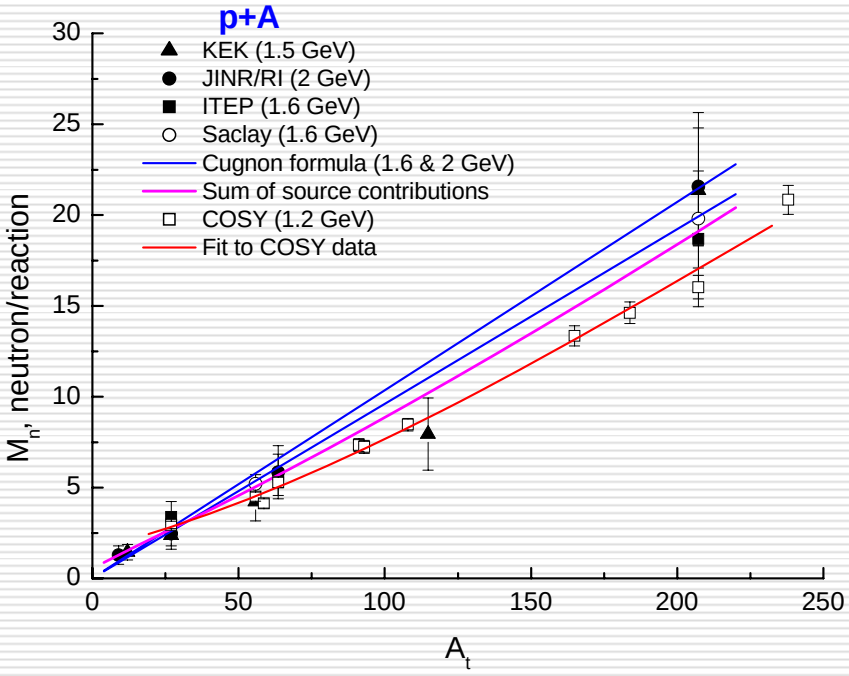
Reaction	Energy (GeV)	*M*n (n/reac.)	Source 2 (%)	Source 3 (%)
p+Pb	2	21.8±3.4	16	22
^{4}He+Pb	4	22.5±3.5	19	23
^{12}C+Pb	24	29.1±4.5	16	26

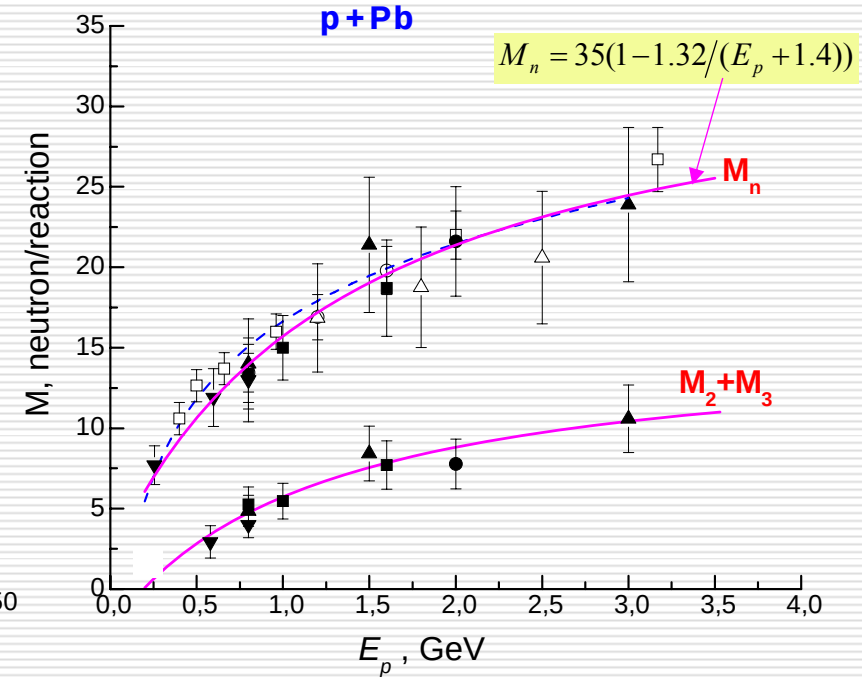
~41% of neutron multiplicity

About 41% of all neutrons are emitted from Hot and Fragmentation Sources and this value is independent of target, projectile and energy in GeV energy range !

Results of MSM analysis

Source contributions to neutron yield





Saturation effect with increasing of proton energy !

CONCLUSION

- New measurements of neutron production cross sections have been carried out in Dubna with beams of p,^{4}He and C at GeV energies.

- Developed MSM with four decay processes (neutron sources) is effective tool for neutron data analysis in high-energy reactions.

- The analysis of TOF neutron data in GeV energy range shows:
  - source temperatures do not depend on beam energy, projectile and target nuclei,
  - neutron and charged particle sources have the same origin,
  - about 41% of mean neutron multiplicity in reactions comes from hot source decay and multifragmentation occurring in central collisions.

- For further progress new experiments with event selection on impact parameter and reaction energy are needed.