# High energy proton emission
# and
# Transport models

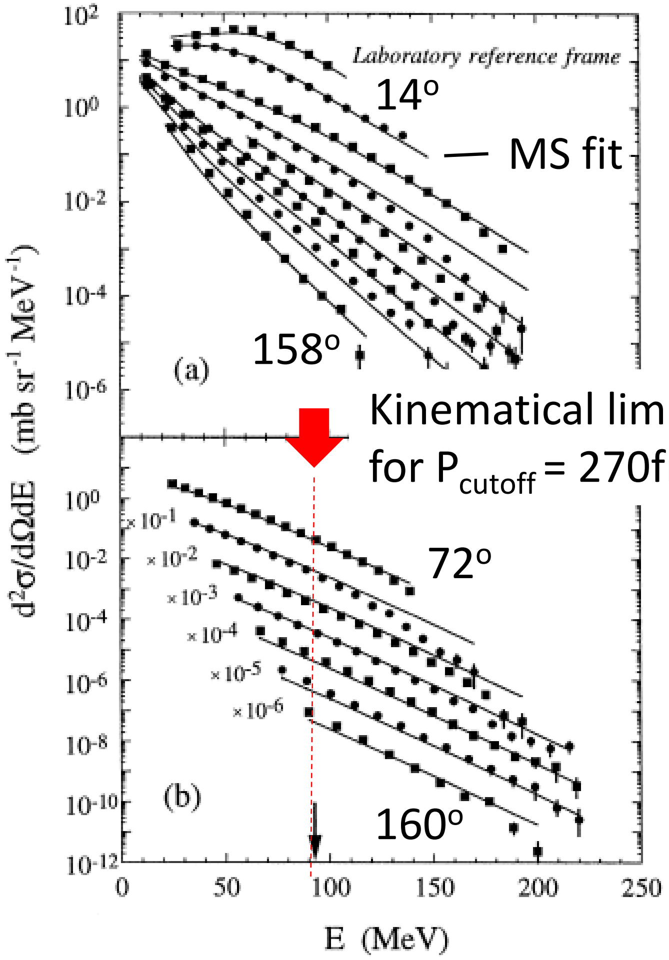
R. Wada
Cyclotron Institute, TAMU

Physics Letters B 471 (2000) 339–345

# High energy proton emission in heavy ion reactions close to the Fermi energy [1]

R. Coniglione [2], P. Sapienza, E. Migneco [3], C. Agodi, R. Alba, G. Bellia [3],
A. Del Zoppo, P. Finocchiaro, K. Loukachine [4], C. Maiolino, P. Piattelli,
D. Santonocito

$^{40}$Ar+$^{51}$V @ 44 A MeV



14°

— MS fit

158°

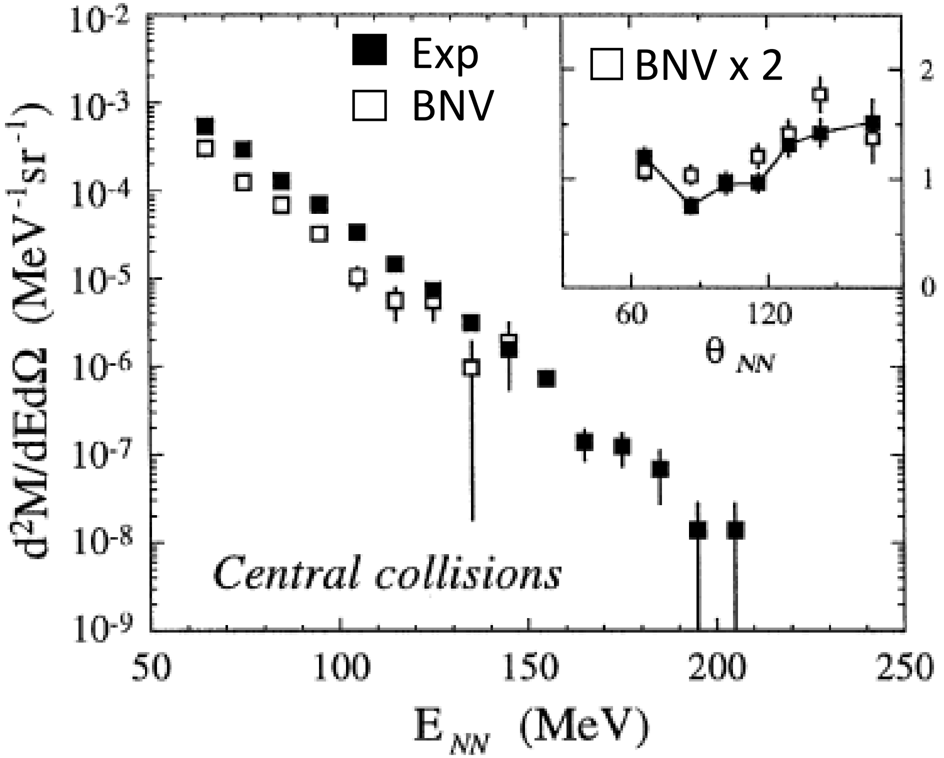
72°

160°

Kinematical limit for $P_{cutoff}$ = 270fm/c.

Boltzmann–Nordheim–Vlasov (BNV)

The calculations are initialized with a sharp cut-off (270fm/c) Fermi momentum distribution and take the free NN cross section.

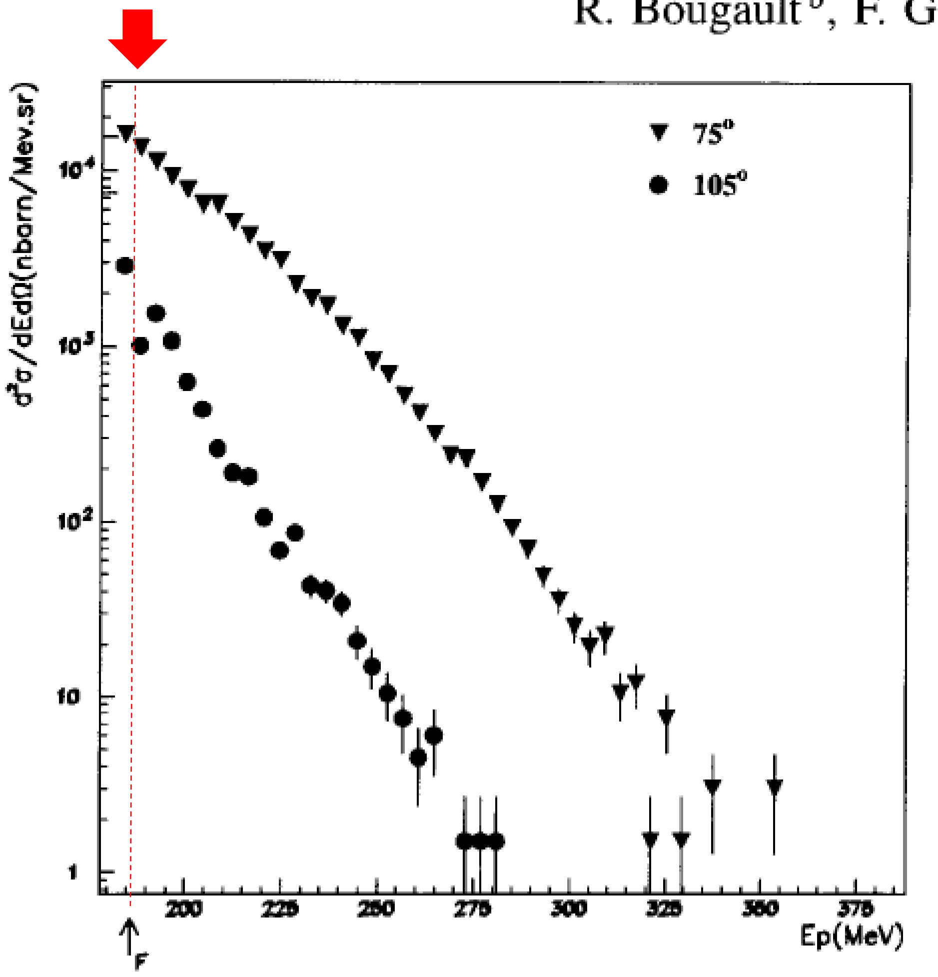


Nuclear Physics A 620 (1997) 81–90

# High transverse momentum proton emission in Ar + Ta collisions at 94 MeV/$u^{\star}$

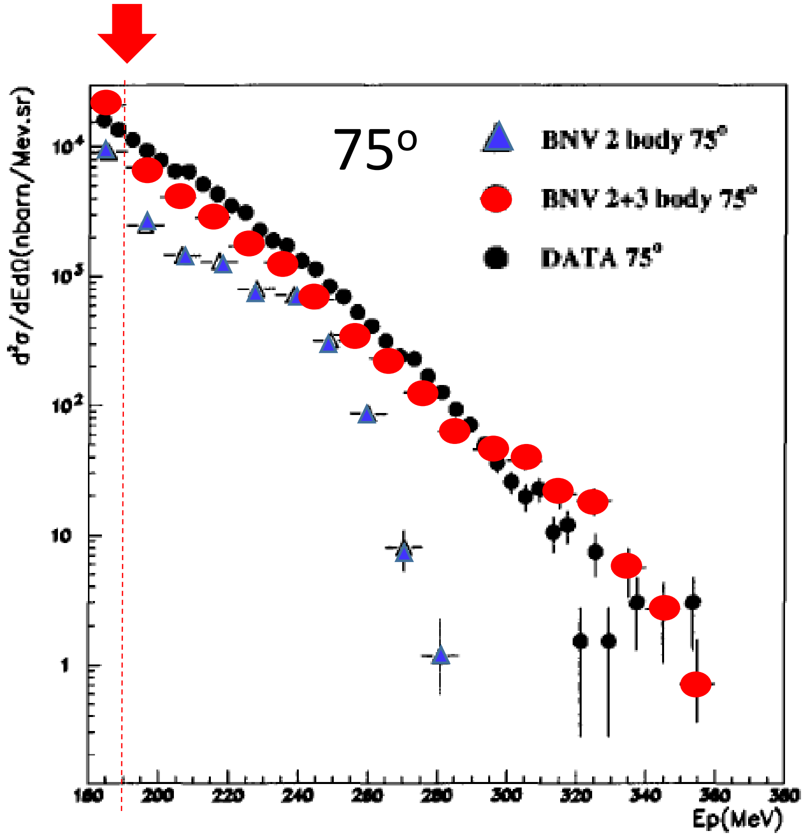
M. Germain[a], P. Eudes[a], F. Guilbault[a], P. Lautridou[a], J.L. Laville[a],
C. Lebrun[a], M. Leguay[a], A. Rahmani[a], T. Reposeur[a]. J. Benlliure[b,1],
R. Bougault[b], F. Gulminelli[b], O. Lopez[b], P. Gagne[c,2], J.P. Wieleczko[c]

Kinematical limit
for $P_{cutoff}$ = 270fm/c.

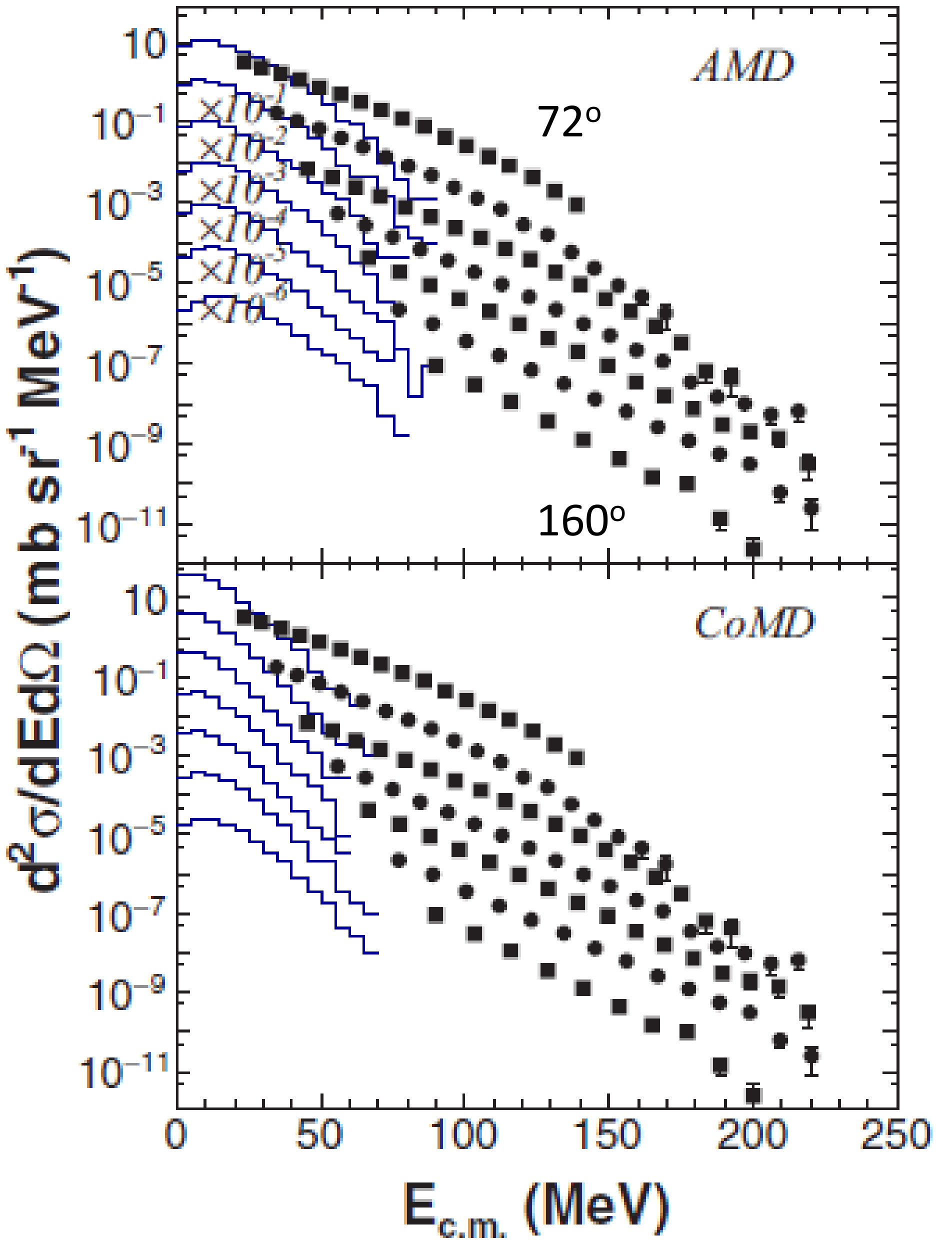


**Boltzmann–Nordheim–Vlasov (BNV)**

We have performed a perturbed calculation: This means that we follow the mean dynamics as given by BNV, and for each two (or three) body Collision, we calculate the Probability that the collision will create a proton of a given energy and solid angle.



$^{40}$Ar+$^{51}$V @ 44 A MeV



AMD: Initial nuclei “frozen”

+

quantum fluctuation

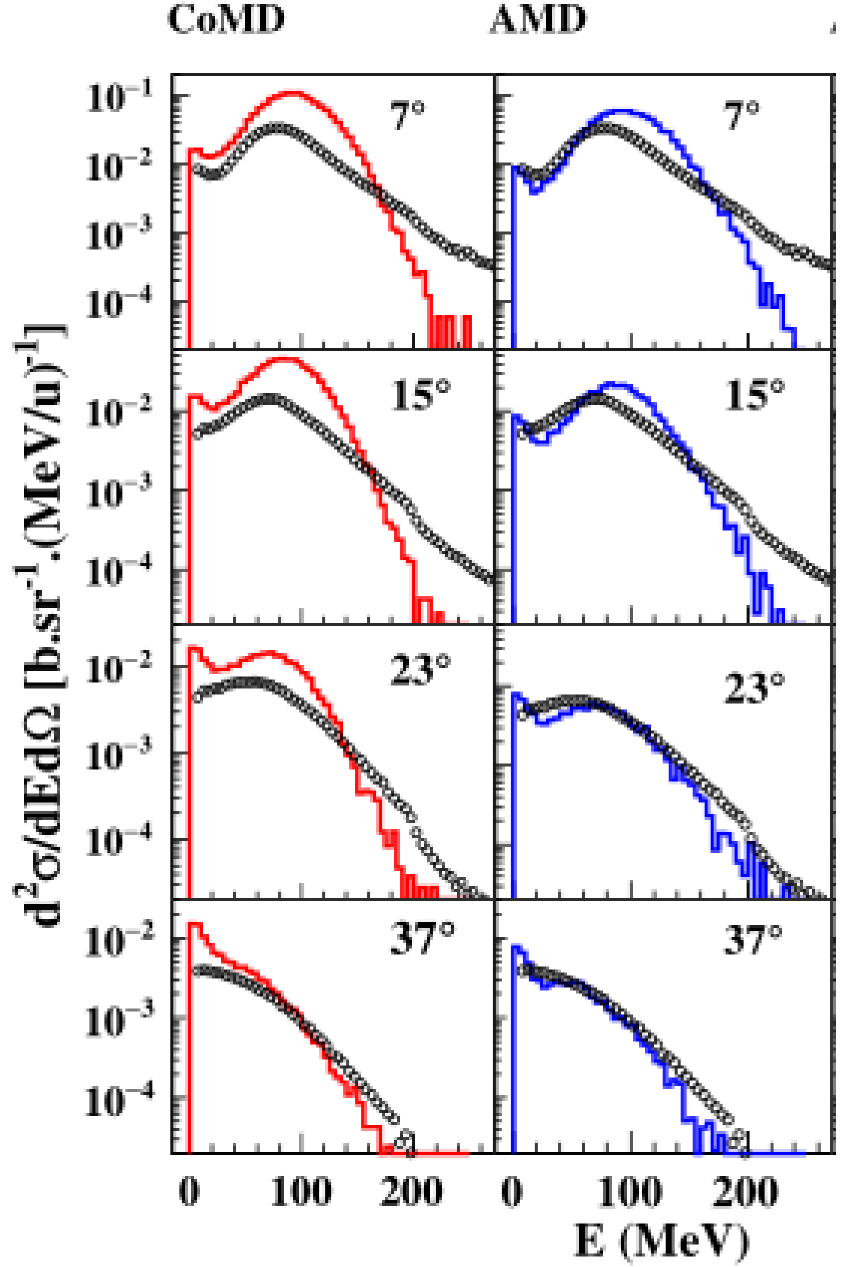
(diffusion process)

CoMD:

Initial nuclei BE=BE_exp

Fermi motion

$^{12}$C+$^{12}$C @ 94 A MeV



# AMD : quantum fluctuation in time evolution of wave packets
# (Diffusion process)

A. Ono, PRC53, 2958 (1996)

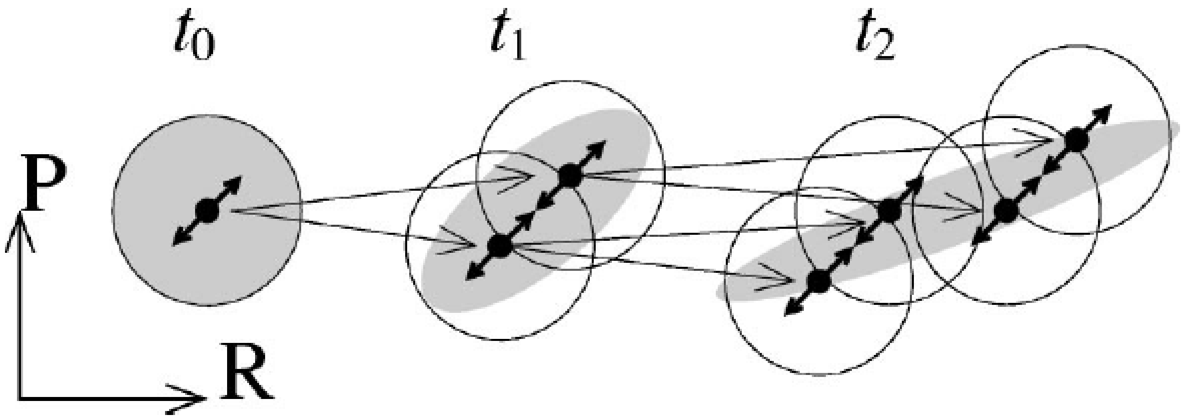
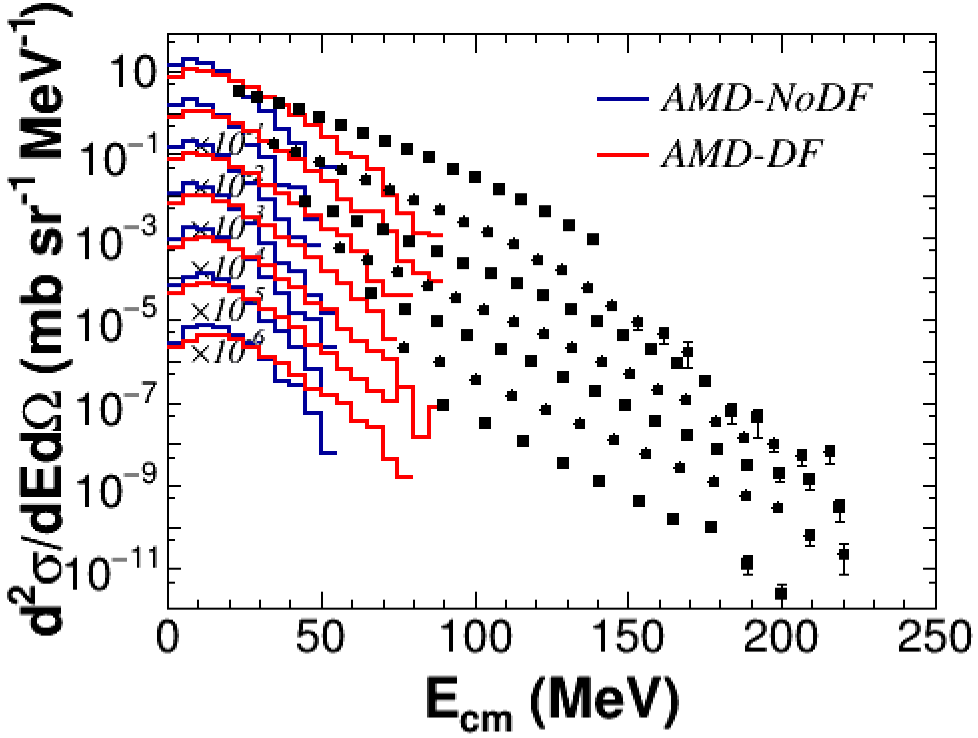


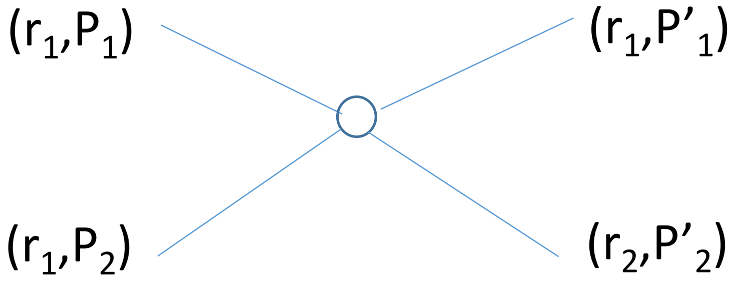
FIG. 1. The branching of the wave packet in AMD/*D* is schematically shown for a free nucleon. The ↔ symbols show the fluctuation to the wave packet centroids. Light gray region shows the exact time evolution of the Wigner function $\bar{f}$.

Fluctuation in collision process

$^{40}$Ar+$^{51}$V @ 44 A MeV



# AMF-FM : Quantum fluctuation in collision process



$(r_1,P_1)$ $(r_1,P'_1)$

$(r_1,P_2)$ $(r_2,P'_2)$

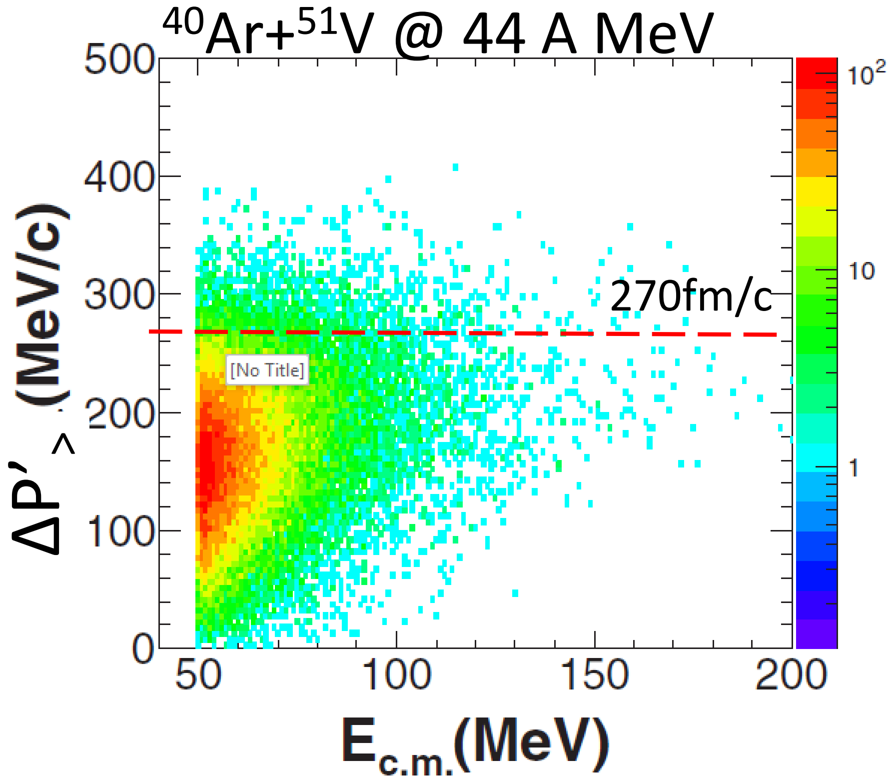
$P_i + \Delta P_i$ (i = 1,2)

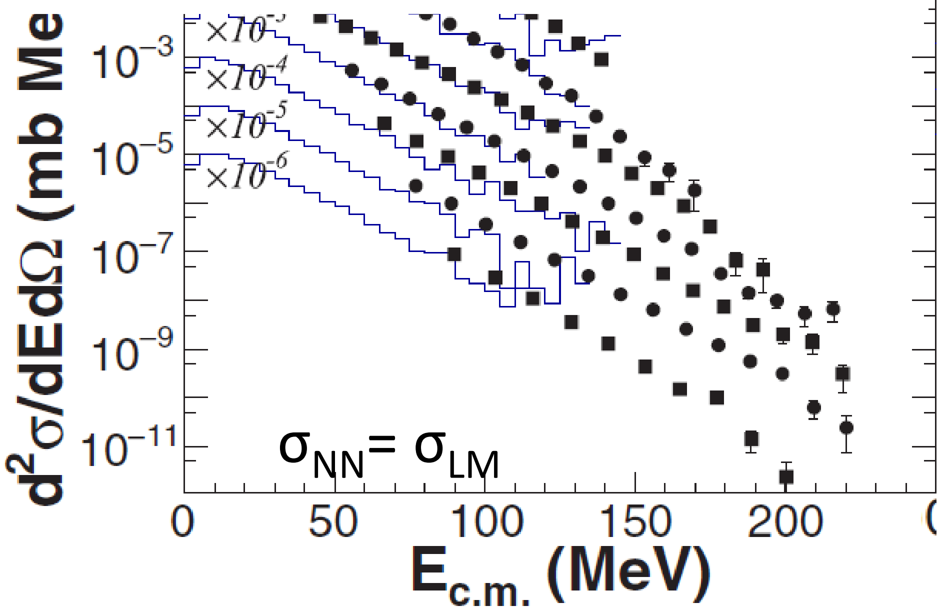
Momentum fluctuation is partially taken into account in the diffusion process.

$$\Delta P_i' = \sqrt{\left(\frac{|\Delta P_i|^2}{2M_0} - T_0\right)2M_0}\,\frac{\Delta P_i}{|\Delta P_i|},$$

$$\Delta P_{i\tau} = \hbar\sqrt{\nu}(\rho_i/\rho_0)^{1/3}G(1),$$

The $T_0 = 3\hbar^2\nu/2M_0 \sim 10$ MeV originally corresponds to the expectation value of the mean energy for the Gaussian distribution,





# Apply AMD-FM at higher energy
## $^{36}$Ar + $^{181}$Ta at 94 A MeV

Germain et al., Nucl. Phys. A620, 81 (1997)

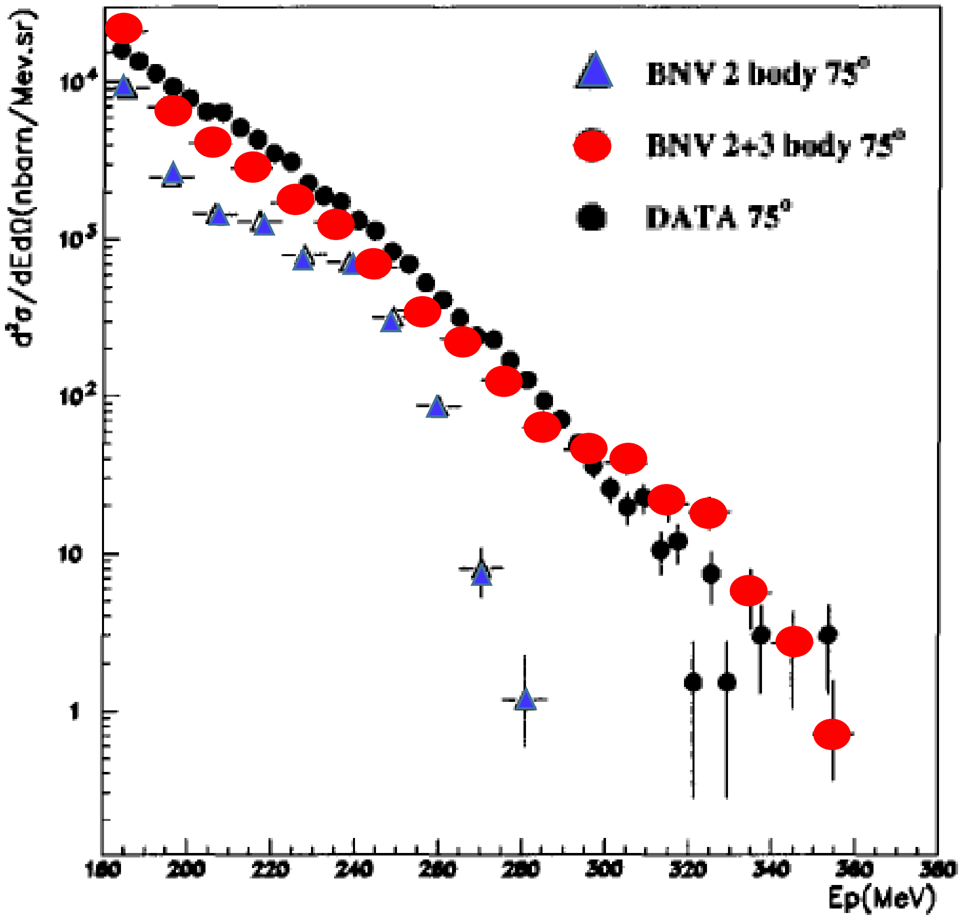
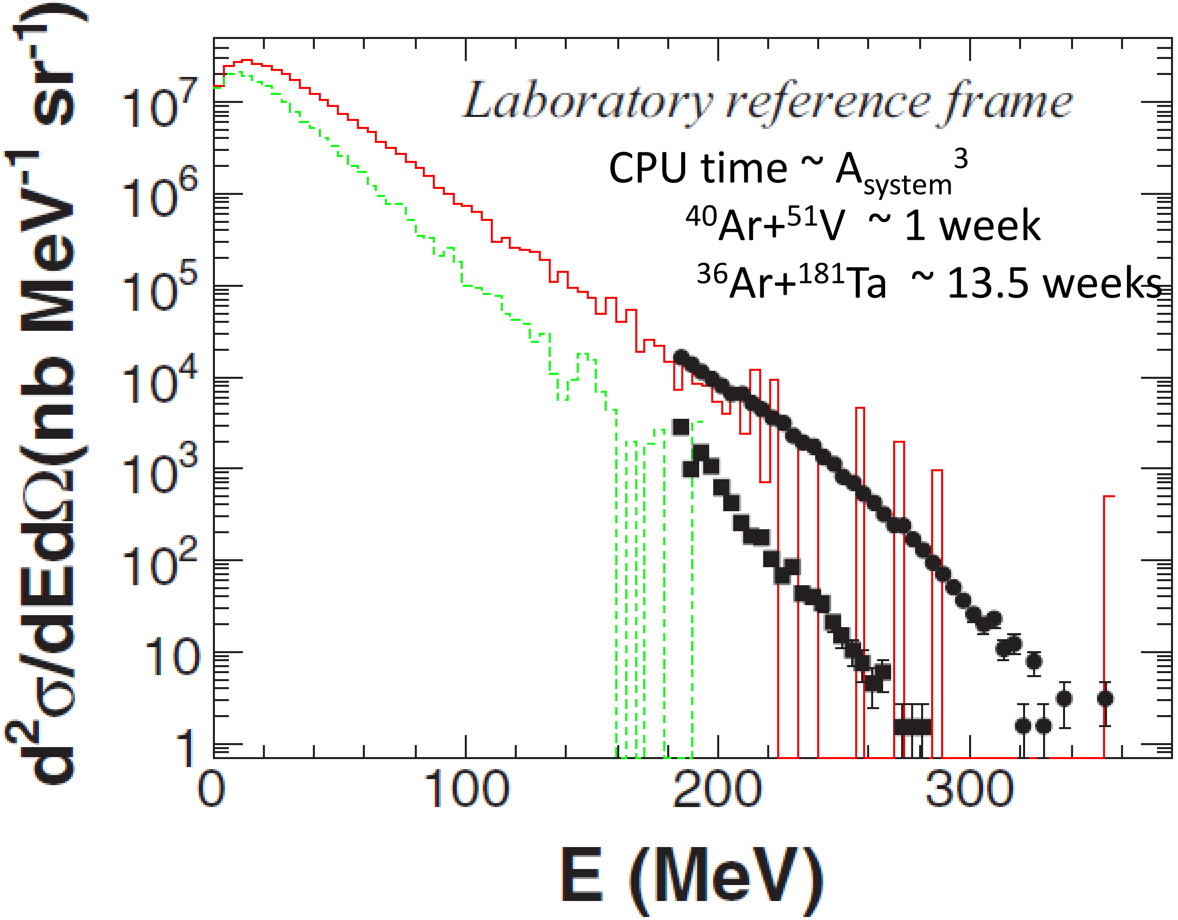


FIG. 10. The energy ($E_{cm}$) versus the sampled momentum for

## AMD-FM



CPU time ~ $A_{system}^3$

$^{40}$Ar+$^{51}$V ~ 1 week

$^{36}$Ar+$^{181}$Ta ~ 13.5 weeks

Up to 100 A MeV, high energy proton emission can be explained by the quantum fluctuation in the diffusion and collision process.

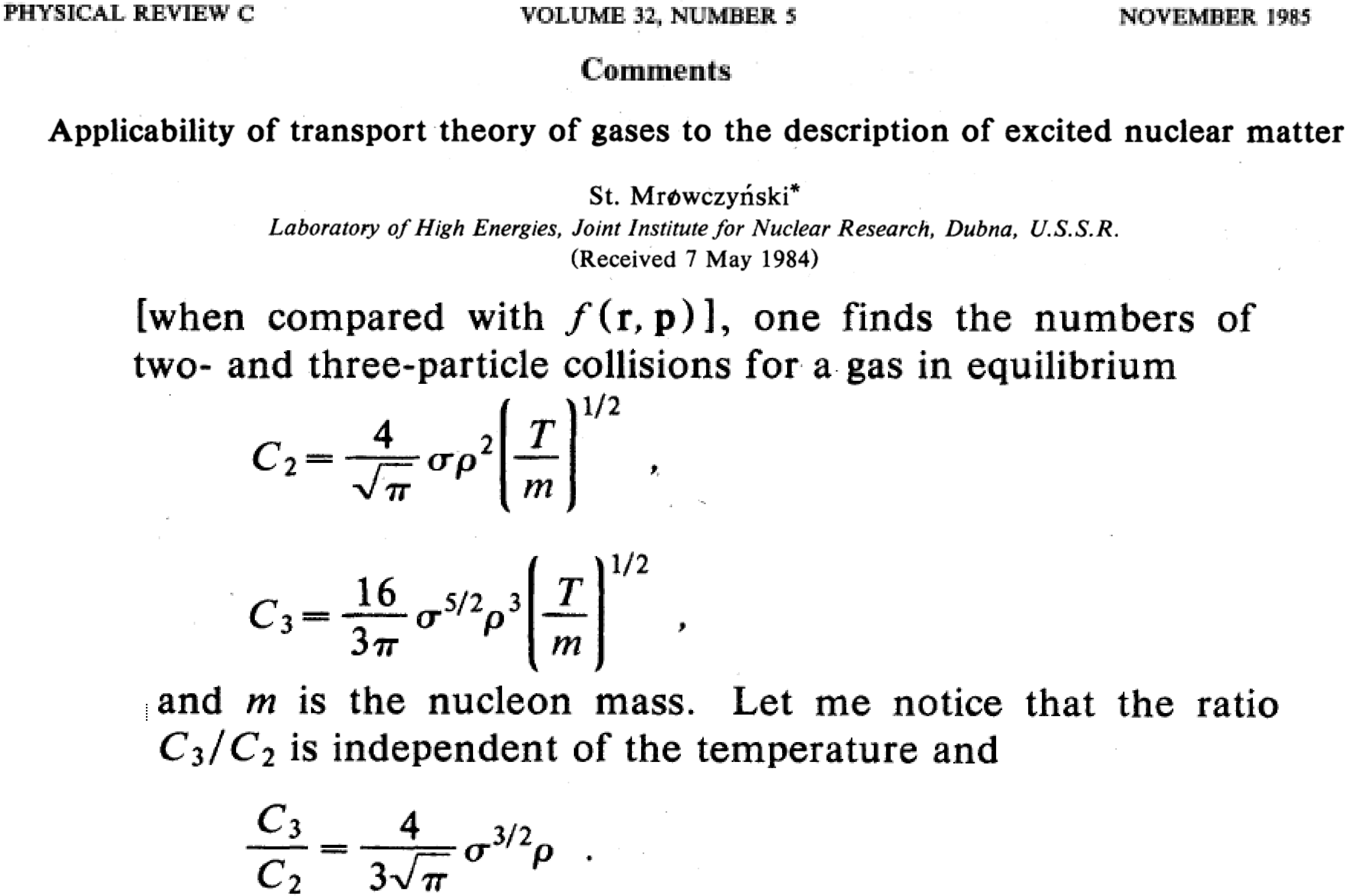
PHYSICAL REVIEW C **94**, 064609 (2016)

# High-energy proton emission and Fermi motion in intermediate-energy heavy-ion collisions

W. Lin (林炜平),[1] X. Liu (刘星泉),[1,*] R. Wada,[1,2,†] M. Huang (黄美容),[1,2] P. Ren (任培培),[1,3] G. Tian (田国玉),[1,3]
F. Luo (罗飞),[1,4] Q. Sun (孙琪),[1,3] Z. Chen (陈志强),[1] G. Q. Xiao (肖国青),[1] R. Han (韩瑞),[1] F. Shi (石福栋),[1]
J. Liu (刘建立),[1] and B. Gou (勾伯兴)[1]

[1] *Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China*
[2] *Cyclotron Institute, Texas A&M University, College Station, Texas 77843, USA*
[3] *University of Chinese Academy of Sciences, Beijing 100049, China*
[4] *University of Science and Technology of China, Hefei 230026, China*

# Higher Energy (100-400 A MeV) ?



PHYSICAL REVIEW C VOLUME 32, NUMBER 5 NOVEMBER 1985

**Comments**

## Applicability of transport theory of gases to the description of excited nuclear matter

St. Mrøwczyński*
*Laboratory of High Energies, Joint Institute for Nuclear Research, Dubna, U.S.S.R.*

(Received 7 May 1984)

[when compared with $f(\mathbf{r},\mathbf{p})$], one finds the numbers of two- and three-particle collisions for a gas in equilibrium

$$C_2=\frac{4}{\sqrt{\pi}}\sigma\rho^2\left(\frac{T}{m}\right)^{1/2} ,$$

$$C_3=\frac{16}{3\pi}\sigma^{5/2}\rho^3\left(\frac{T}{m}\right)^{1/2} ,$$

and $m$ is the nucleon mass. Let me notice that the ratio $C_3/C_2$ is independent of the temperature and

$$\frac{C_3}{C_2}=\frac{4}{3\sqrt{\pi}}\sigma^{3/2}\rho .$$

# 3 body collisions in AMD-FM

NN interaction → mean field propagation+ NN collision term

NNN interaction → (mean field propagation)+ 3N collision term

3N collision term (A. Bonasera et al., Phys. Rep. 243, 1 (1994) )

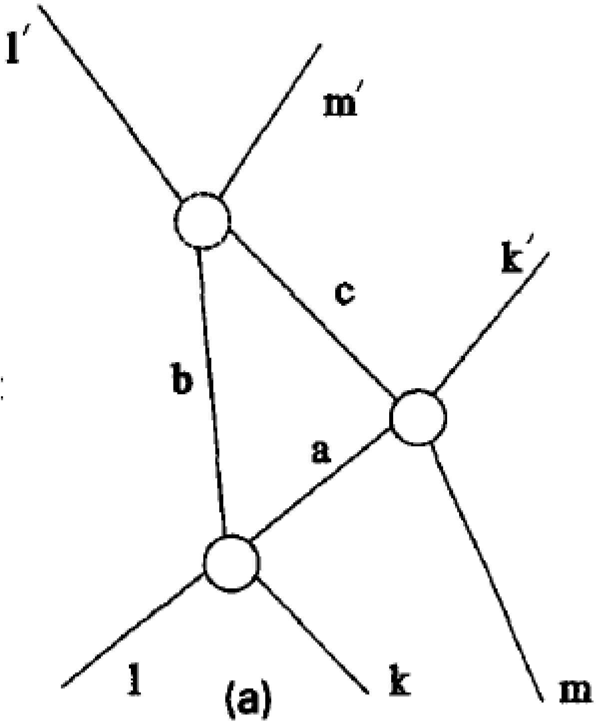
3 consecutive NN collisions

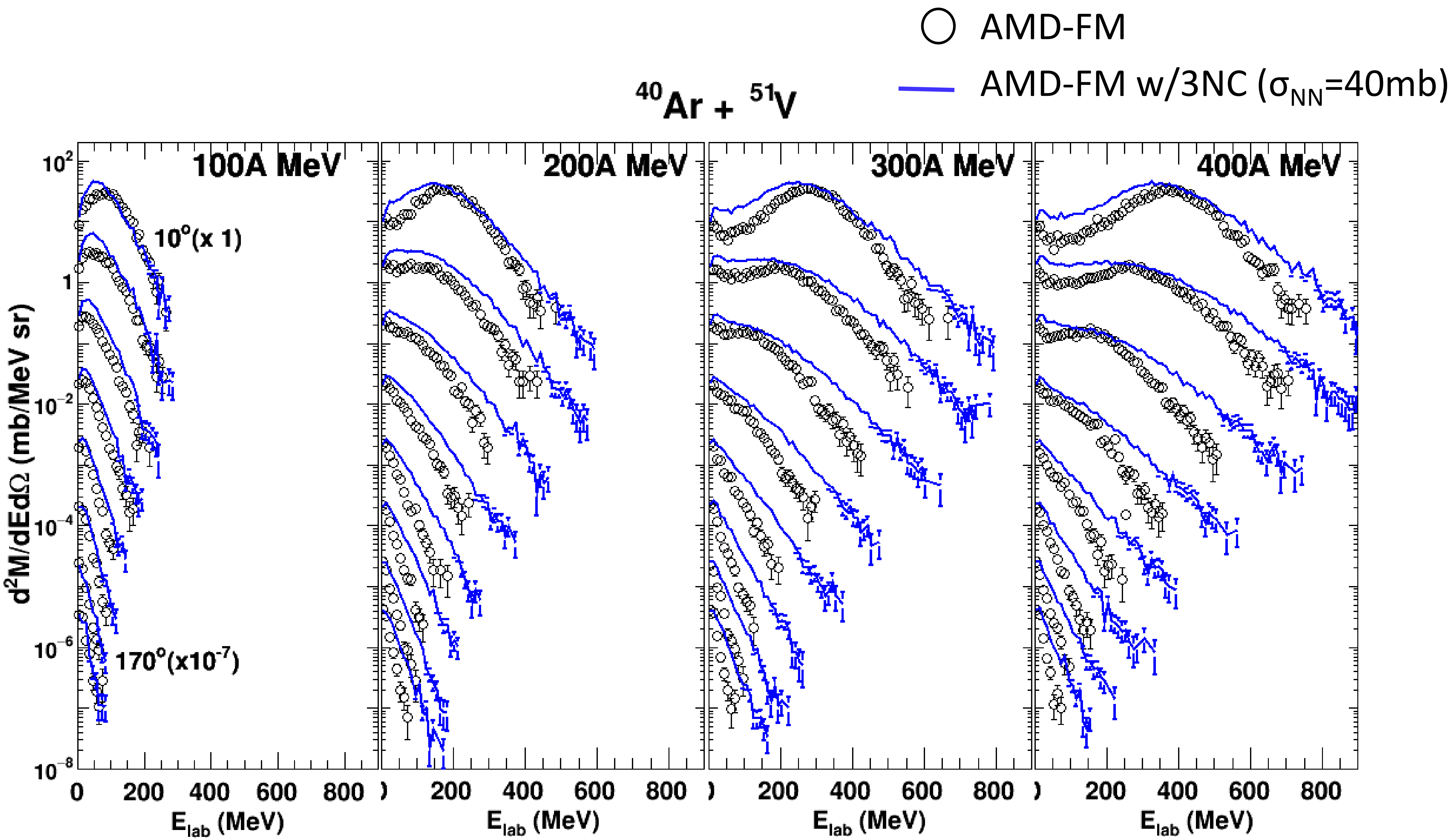
At each collision, Fermi boost is taken into account
in same way as AMD-FM;

$P'_i = P_i + \Delta P'_i$ (i = 1,2)

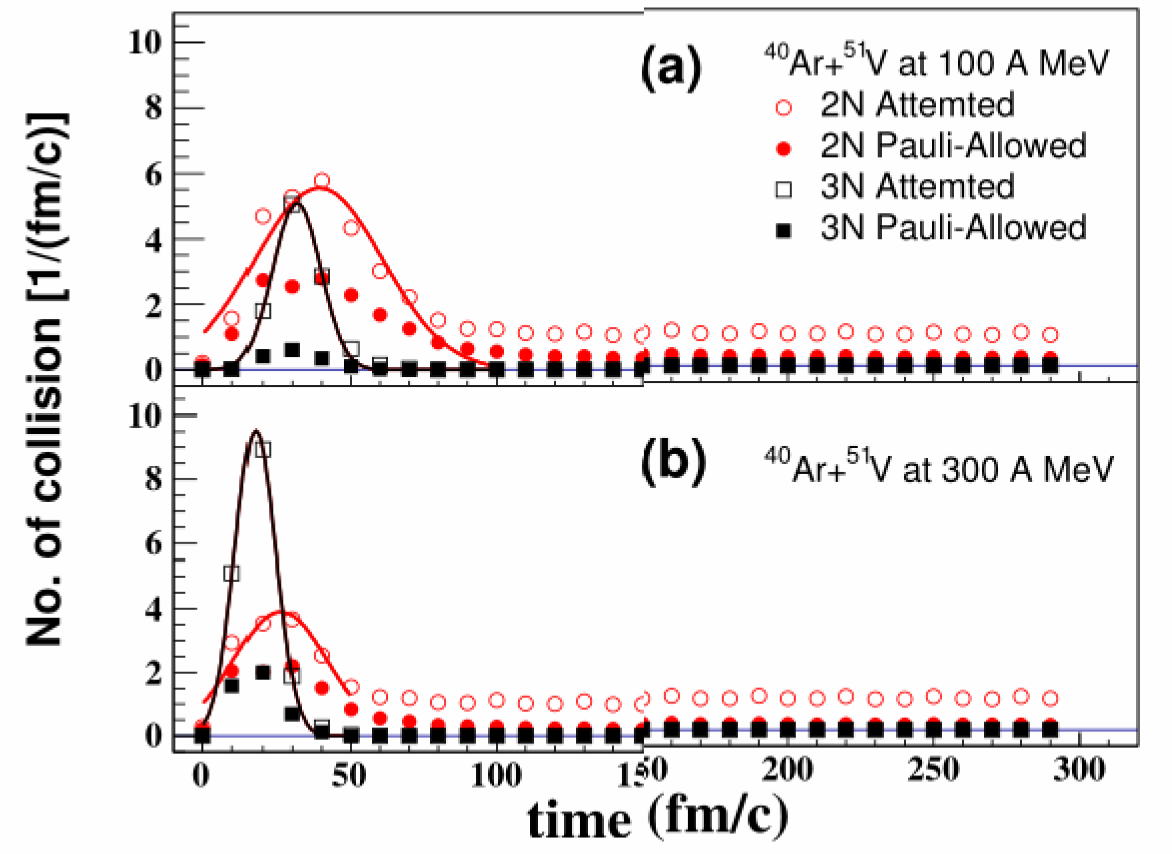
$$\Delta P'_i = \sqrt{\left(\frac{|\Delta P_i|^2}{2M_0} - T_0\right)2M_0}\,\frac{\Delta P_i}{|\Delta P_i|},$$

$$\Delta P_{i\tau} = \hbar\sqrt{\nu}(\rho_i/\rho_0)^{1/3}G(1),$$

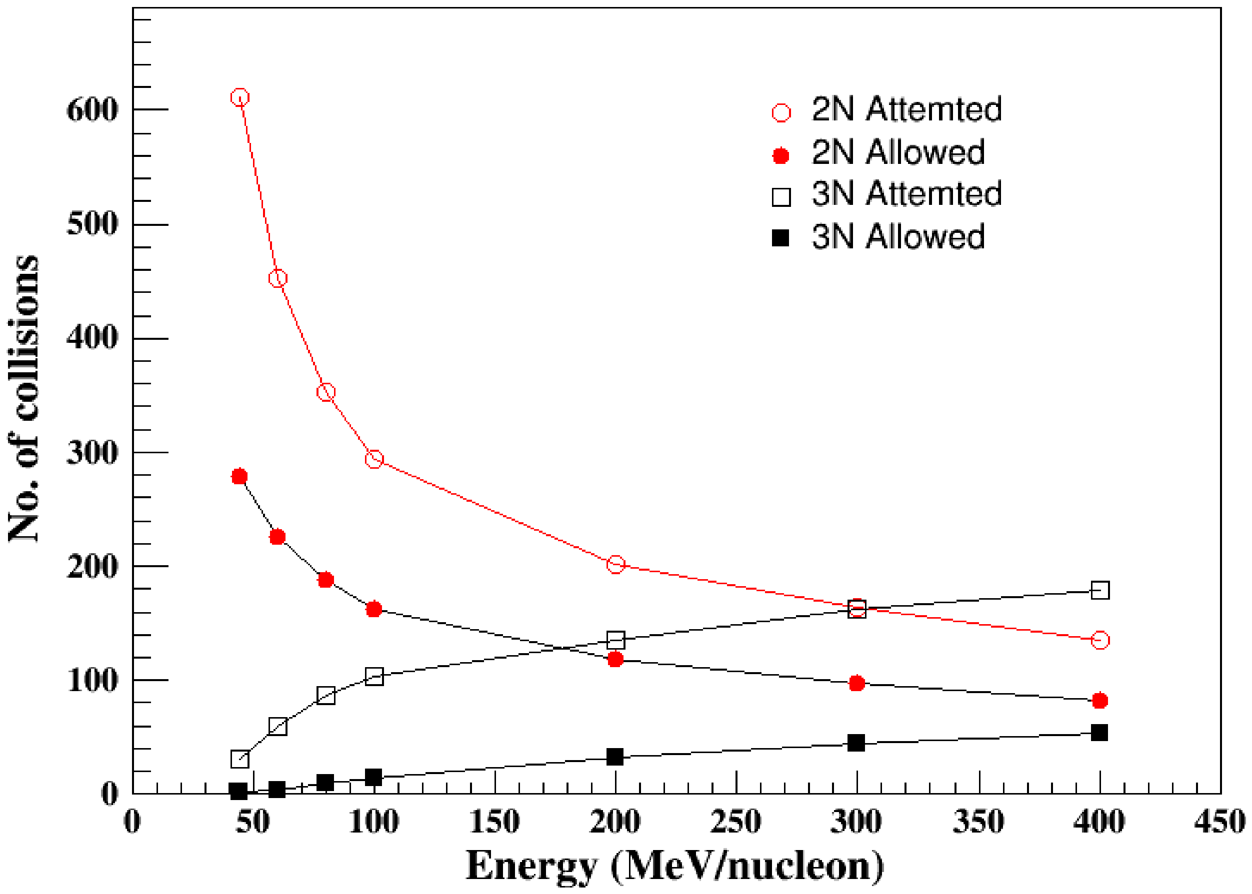



○ AMD-FM
AMD-FM w/3NC ($\sigma_{NN}$=40mb)
$^{40}$Ar + $^{51}$V
100A MeV
200A MeV
300A MeV
400A MeV
10°(x 1)
170°(x10$^{-7}$)
$d^2M/dEd\Omega$ (mb/MeV sr)
$10^2$
1
$10^{-2}$
$10^{-4}$
$10^{-6}$
$10^{-8}$
0
200
400
600
800
$E_{lab}$ (MeV)

Collision time and number



Number of collisions vs incident energy



Summary

1. High energy proton emission below 50A MeV can be explained by AMD with a two nucleon collision term with Fermi boost together with the diffusion process.
2. 3N collisions play a significant role for the high energy proton emissions above ~100A MeV heavy ion collisions.
3 3N high energy proton production is very localized at the reaction time of high density and high temperature, and this will provide a probe for a hot-high density nuclear matter study.