PARTICLE

YIELDS IN EQUILIBRIUM

$$N_x = \int d^3p \frac{dN_x}{d^3p_x} = \frac{V}{(2\pi)^3} g \, e^{(\mu_x + B_x)/T}$$

$$\times \int d^3p \, e^{-p^2/2m_xT}$$

$$\int e^{-\alpha x^2} = \sqrt{\frac{\pi}{\alpha}}$$

$$(\pi \, 2m_xT)^{3/2}$$

$$\boxed{N_x = gV \left(\frac{m_xT}{2\pi}\right)^{3/2} e^{(\mu_x + B_x)/T}}$$

$$\mu_x = N_x \mu_n + Z_x \mu_p$$

V, T, μ_n, μ_p

ALL YIELDS

YIELD RATIO

$$\frac{N_x}{N_y} \leftarrow T, \mu_n, \mu_p$$

V DROPS OUT!

$\mu_n \simeq \mu_p \simeq \mu_N$

$T, \mu_N \leftarrow$ 2 PARAMETERS ONLY

FREEZE-OUT PARAMETERS

CHEMICAL FREEZE-OUT

$T_{kin} \lesssim T_{chem}$

SYSTEM COOLS AS IT EXPANDS

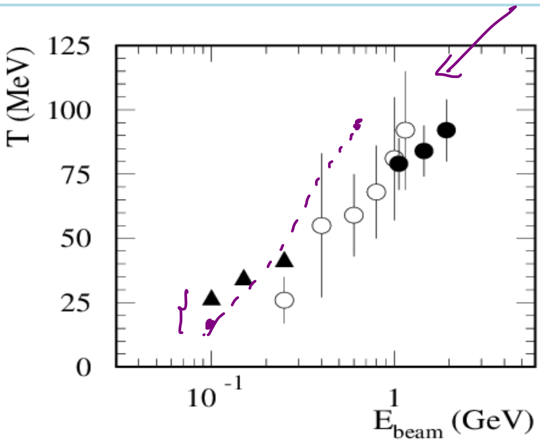
T_{kin} – DESCRIBES SPECTRA

ELASTIC PROCESSES CONTINUE LONGER THAN INELASTIC

SYMMETRIC COLLISION AT E_{LAB}/A

$$\frac{E_{CM}}{A} = \frac{E_{LAB}}{4A} = \frac{3}{2}T \qquad T = \frac{2}{3}\frac{E_{LAB}}{4A} = \frac{1}{6}\frac{E_{LAB}}{A}$$

PRODUCTION OF NEW PARTICLES ESPECIALLY π MESONS

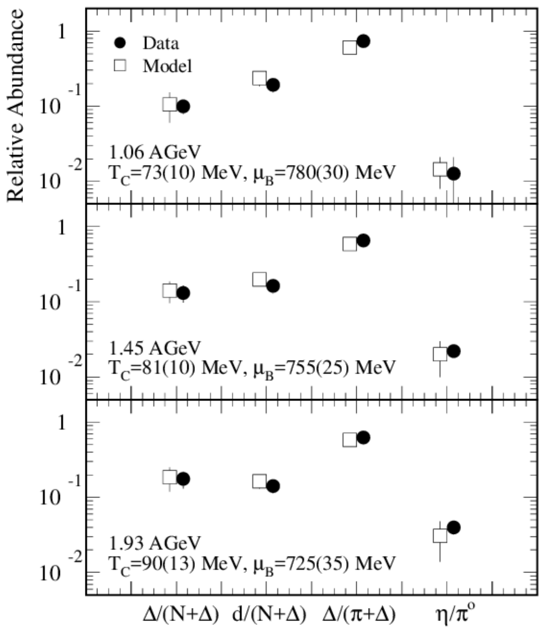


HONG FROM FOPI

$$E_{cm} = \frac{E_{lab}}{4} = \mathcal{N}\frac{3}{2}T$$

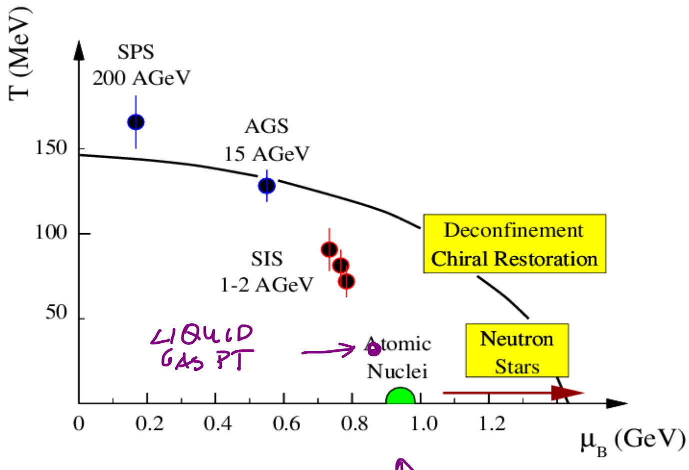
$$T = \frac{A}{\mathcal{N}}\frac{E_{lab}}{6A} \qquad \frac{E_{lab}}{4A} = \frac{\mathcal{N}}{A}\frac{3}{2}T$$

$T \lesssim 170$ MeV ← FREEZE-OUT NEVER EXCEEDS ABOUT 170 MeV



Au+Au ?

$$\mu_X \sim \underbrace{m_X} + \frac{p_x^2}{2m_x T}$$



$\uparrow$

$1\,m$

$e^{\mu/T}$ ACTIVITY

ENTROPY IN A NUCLEONIC GAS

$$S = A\left[\frac{5}{2} - \frac{\mu}{T}\right]$$ SACKUR TETRODE

$$\frac{S}{A} = \frac{5}{2} - \frac{\mu_N}{T}$$ $\leftarrow$ CAN BE DETERMINED FROM PARTICLE RATIOS

$g = 3 = 2s+1 \qquad s = 1$

$$N_d = V\, 3\left(\frac{m_d T}{2\pi}\right)^{3/2} \times e^{(\mu_d + B_d)/T}$$

$$N_p = V\,2\left(\frac{m_p T}{2\pi}\right)^{3/2} \times e^{\mu_N/T}$$

$$\mu_d = 2\mu_N \qquad m_d \simeq 2m_N \qquad B_d/T \simeq 0$$

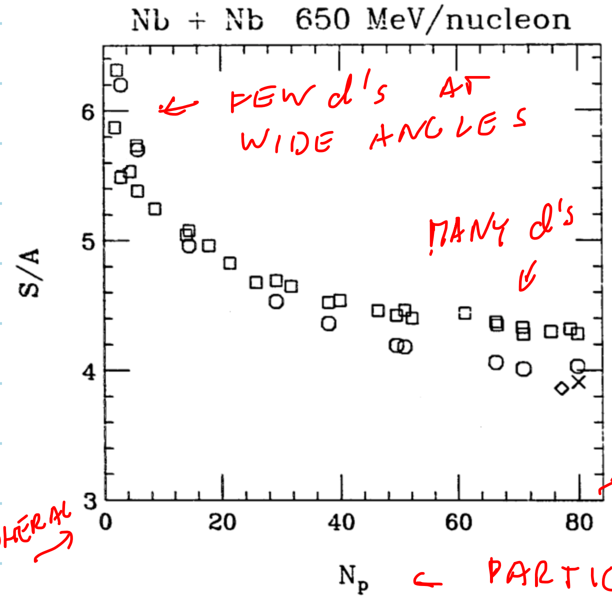
$$\frac{N_d}{N_p} = e^{(2\mu_N - \mu_N)/T}\left(\frac{m_d}{m_p}\right)^{3/2} \times \frac{3}{2}$$

$$= e^{\mu_N/T}\,\frac{3}{2}\,2^{3/2} = 3\sqrt{2}\,e^{\mu_N/T}$$

$$e^{\mu N/T} = \frac{N_d}{3\sqrt{2}\,N_p}$$

$$\left\{ \frac{S}{A} \simeq \frac{5}{2} - \log\left(\frac{N_d}{3\sqrt{2}\,N_p}\right) \right.$$

$$\boxed{\frac{S}{A} = 3.95 - \log \frac{N_d}{N_p}}$$



AT WIDE ANGLES

$\frac{N_d}{N_p}$

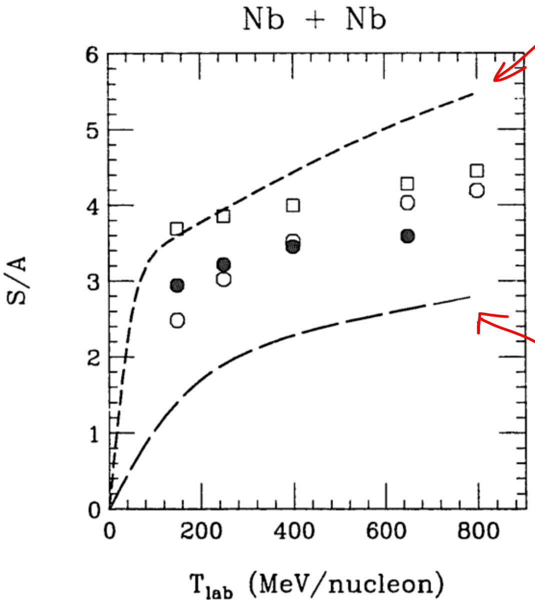
CENTRAL — MOST PROTONS AT WIDE ANGLES

MOST PERIPHERAL

N_p ← PARTICIPANT PROTONS

CENTRAL

Nb + Nb



PURE FIREBALL MODEL

REALISTIC ENTROPY EXTRACTED FROM DATA & SEMIREALISTIC MODELS

HYDRODYNAMIC MODEL

← SHOCK FRONTS

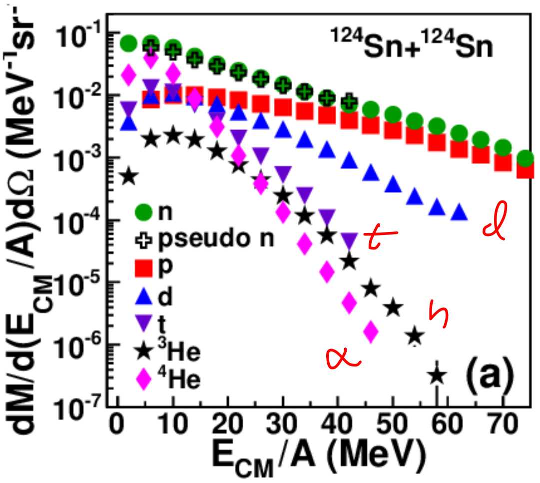
v_{cm}

v_{cm}

STOPPED MATTER

SCALING OF THE SPECTRA CAN BE USED TO DEDUCE SPECTRA THAT ARE NOT MEASURED

?. NEUTRON MEASUREMENTS ?



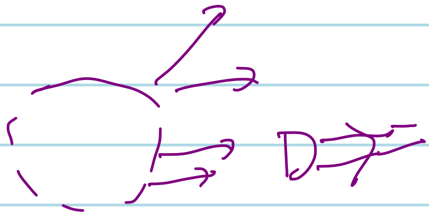
50 MeV/nucl
CHAJECKI

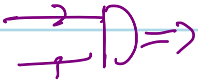
GREEN SPECTRA
n MEASURED DIRECTLY

CROSSES - RECONSTRUCTED

↑ ENERGY IN THE SYSTEM CM
~ PERPENDICULAR DIRECTION OF EMISSION

COALESCENCE MODEL





PARTICLES COMING OUT CLOSE TO EACH OTHER IN VELOCITY SPACE OR MOMENTUM (PER NUCLEON) CAN JOIN TOGETHER & COME OUT AS ONE FRAGMENT

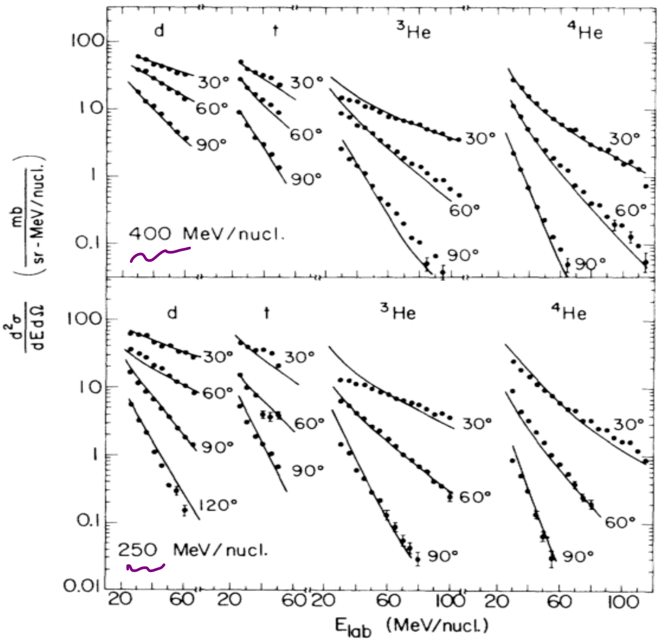
$$\frac{dN_x}{d^3p} \propto \left[\frac{dN_p}{d^3(p/A)}\right]^{Z_x} \cdot \left[\frac{dN_n}{d^3(p/A)}\right]^{N_x}$$

NO ASSUMPTION ON THE FORM OF $\frac{dN_p}{d^3(p/A)}$ OR $\frac{dN_n}{d^3(p/A)}$

THERMAL MODEL YIELDS / RESULTS OF THE COALESCENCE MODEL

BUT THE CONVERSE IS NOT TRUE

? SUPERPOSITION OF MANY THERMAL SOURCES POSSIBLE ?



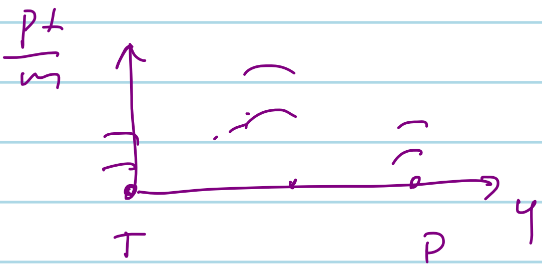
Ne + U COLLISIONS

GUTBROD

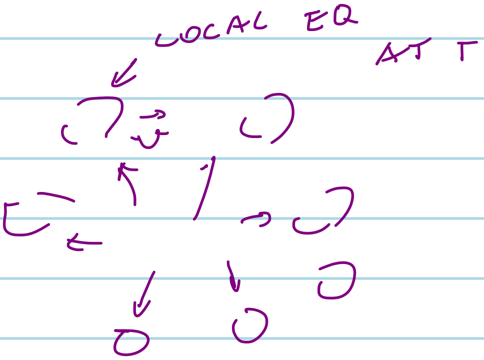
DATA – POINTS

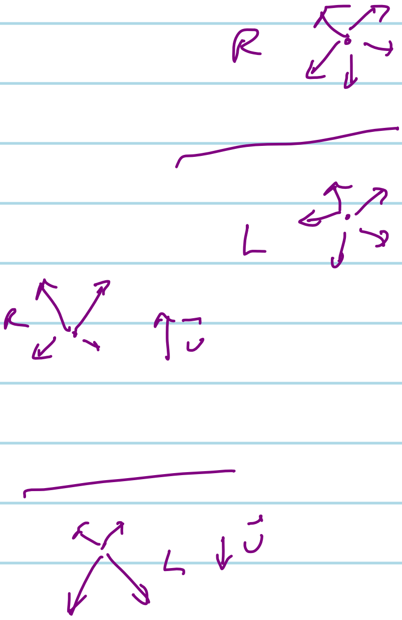
LINES – MODEL UPON INTERPOLATION OF PROTON DATA

SOURCES MOVING AT FINITE VELOCITY RELATIVE TO EACH OTHER



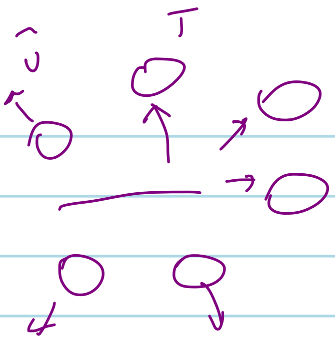
? SYSTEM COOLS AS IT EXPANDS ?





COLLECTIVE MOTION

CORRELATION BETWEEN VELOCITIES & POSITION



DISTRIBUTION OF COLLECTIVE VELOCITIES

$\vec{u} = \vec{u}(\vec{r})$

T

$$\frac{dN_x}{dp^3} = \int d^3r \, \frac{g}{(2\pi)^3} \, e^{\left[\mu_x + B_x - \frac{(\vec{p} - m\vec{u}(\vec{r}))^2}{2m}\right]/T}$$

INSTEAD OF V

WE MAY HAVE

$\vec{u} \equiv \vec{u}_p$ OR $\vec{u} \equiv \vec{u}_T$

$\vec{u} \equiv \vec{u}_{cm}$

? WHAT ABOUT $\vec{u}$ WITH TRANSVERSE COMPONENTS

? $\Rightarrow$ DIFFERENT PARTICLES DIFFERENTLY AFFECTED

$$\left\langle \frac{p^2}{2m_x} \right\rangle = \left\langle \frac{(\vec{p} - m_x\vec{u} + m_x\vec{u})^2}{2m_x} \right\rangle$$

$$= \left\langle \frac{(\vec{p} - m_x\vec{u})^2}{2m_x} \right\rangle + \frac{\langle (m_x \vec{u})^2 \rangle}{2m_x}$$

LOCAL THERMAL MOMENTUM

$$\overset{\parallel}{\frac{3}{2}T} + \frac{\langle \overbrace{(\vec{p} - m_x\vec{u})} \, m_x\vec{u} \rangle}{2m_x}$$

FIXED DIRECTION FOR LOCATION

$\overset{\parallel}{0}$

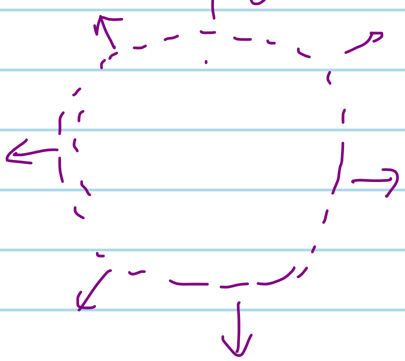
$$\langle E \rangle = \left\langle \frac{p^2}{2m_x} \right\rangle = \frac{3}{2}T + \frac{m_x}{2}\langle \vec{u}^{\,2} \rangle$$

LIGHT PARTICLES BETTER TEST THERMAL MOTION THAN HEAVY

HEAVY PARTICLES BETTER TEST COLLECTIVE VELOCITY DISTRIBUTION

? MODEL FOR SPECTRA

$\uparrow \vec{v}$



EXPANDING SHELL

$v \leftarrow$ ONE VALUE

$$\frac{dN}{d^3p} \propto \int d\Omega_{\vec{v}} \; e^{-(\vec{p}-m\vec{v})^2/2mT}$$

θ: ANGLE BTW $\vec{p}$ & $\vec{v}$

$$\propto \int d\cos\theta \; e^{-\frac{p^2}{2mT} + \frac{mpv}{mT}\cos\theta}$$

$$\propto e^{-\frac{p^2}{2mT}} \frac{T}{pv} \left[e^{\frac{pv}{T}} - e^{-\frac{pv}{T}} \right]$$

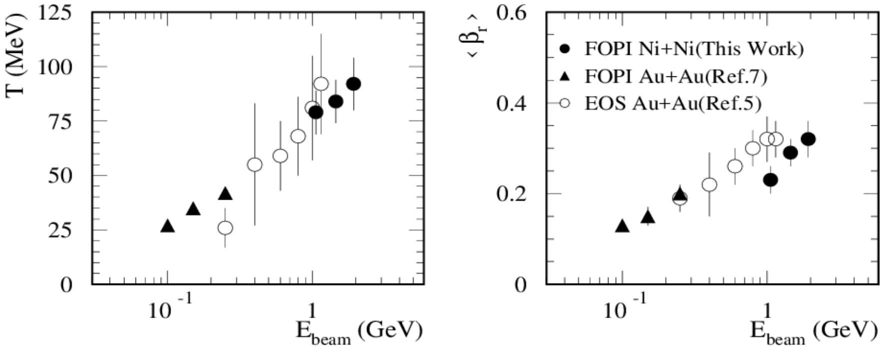
$$\frac{dN}{d^3p} \propto e^{-\frac{p^2}{2mT}} \frac{\sinh\left(\frac{pv}{T}\right)}{p}$$

SPECTRA FITTED WITH v, T, μ

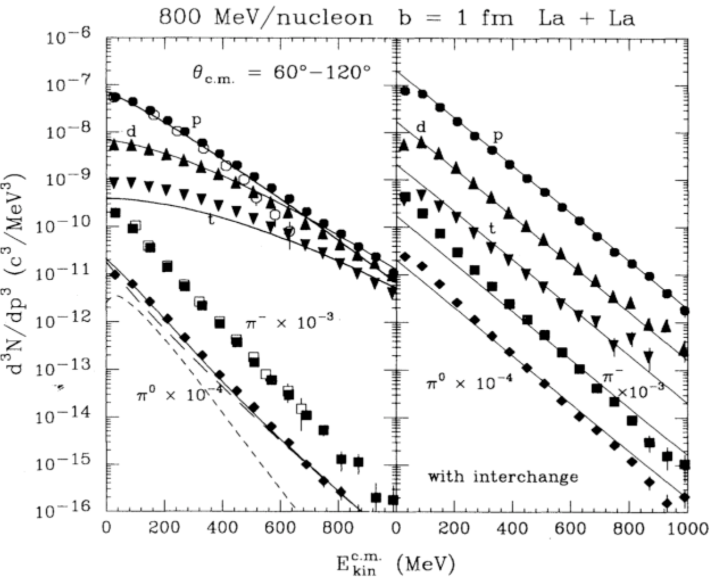
YIELDS NOT CHANGED BY v!

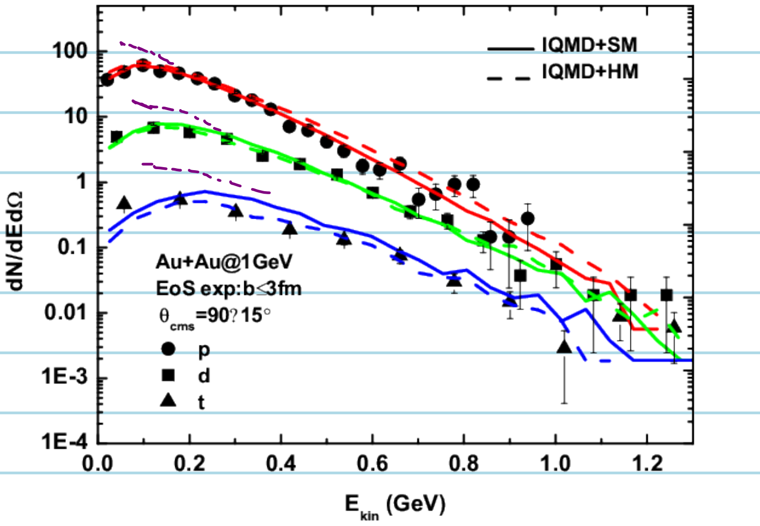
ONLY SPECTRA

HONG
FOPI



$\leftarrow \frac{v}{c}$





SPECTRA IMPACTED BY COLLECTIVE EXPANSION

GET SOFTER SLOPE AS MASS INCREASES WITH MORE CURVATURE

? GAUSSIAN DISTRIBUTION OF COLLECTIVE VELOCITIES ?

$$\frac{dN}{d^3p} \overset{?}{\propto} \int d^3v \; e^{-v^2/2v_0^2} \; e^{-(\bar{p}-m\bar{v})^2/2mT}$$

$$\propto e^{-p^2/2m(T+mv_0^2)}$$

CONVOLUTION OF GAUSSIANS YIELDS A GAUSSIAN

→ SPECTRUM EXPONENTIAL
→ EFFECTIVE TEMPERATURE CHANGES W/ MASS m

DATA DEMAND ABRUPTLY CHANGING VELOCITY DISTRIBUTION!