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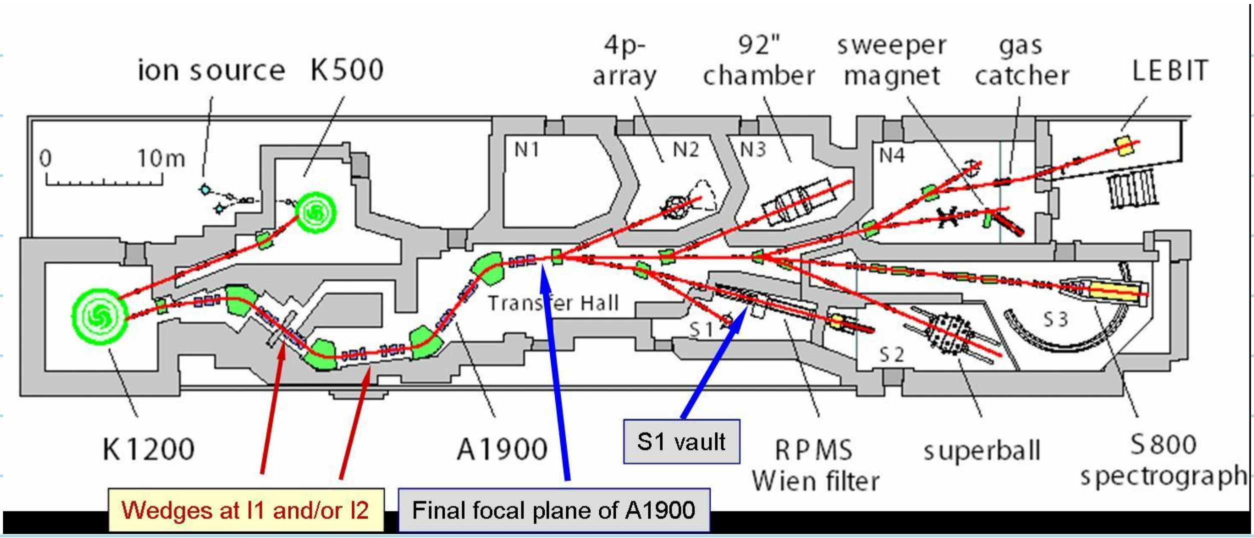
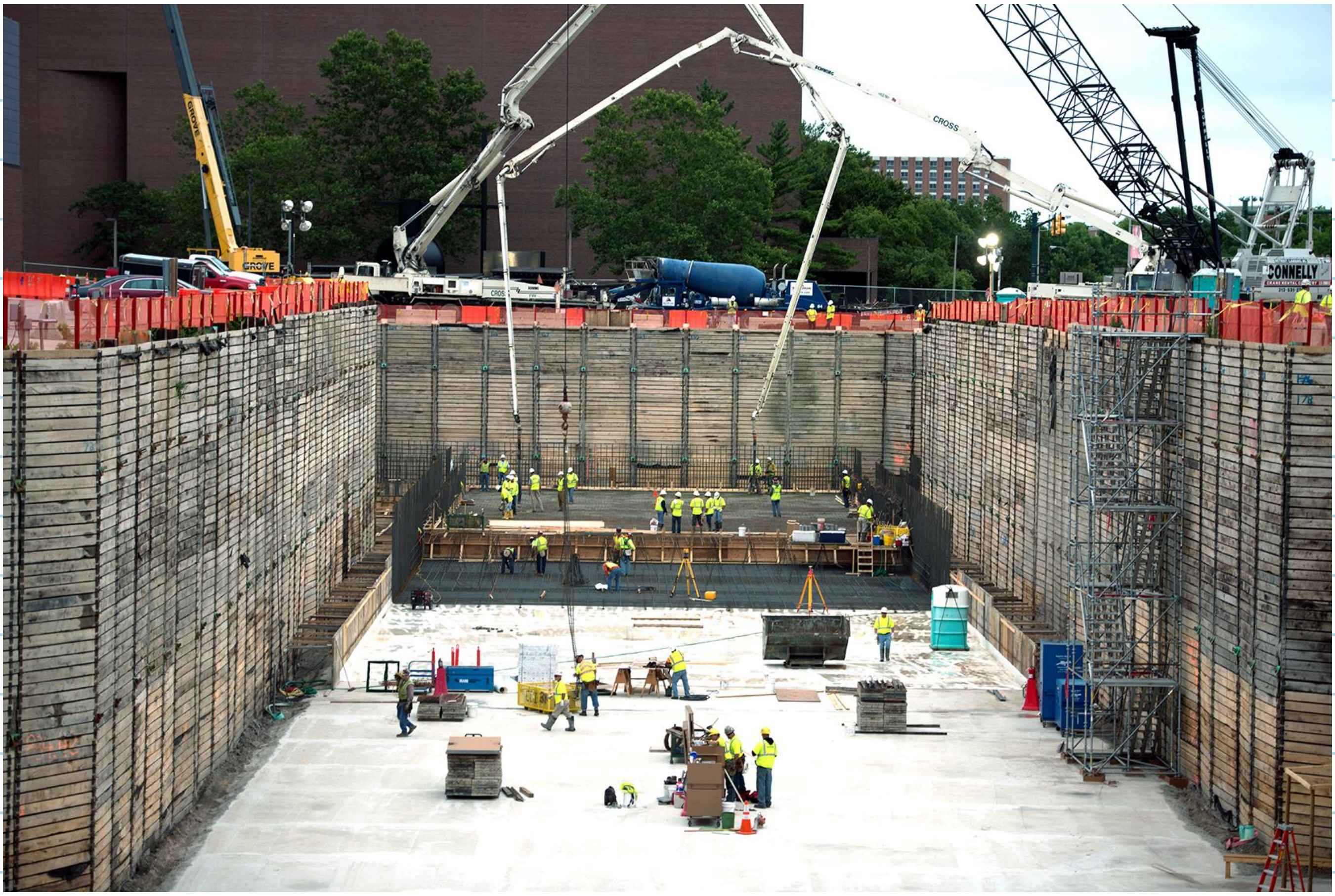
MICHIGAN STATE UNIV.

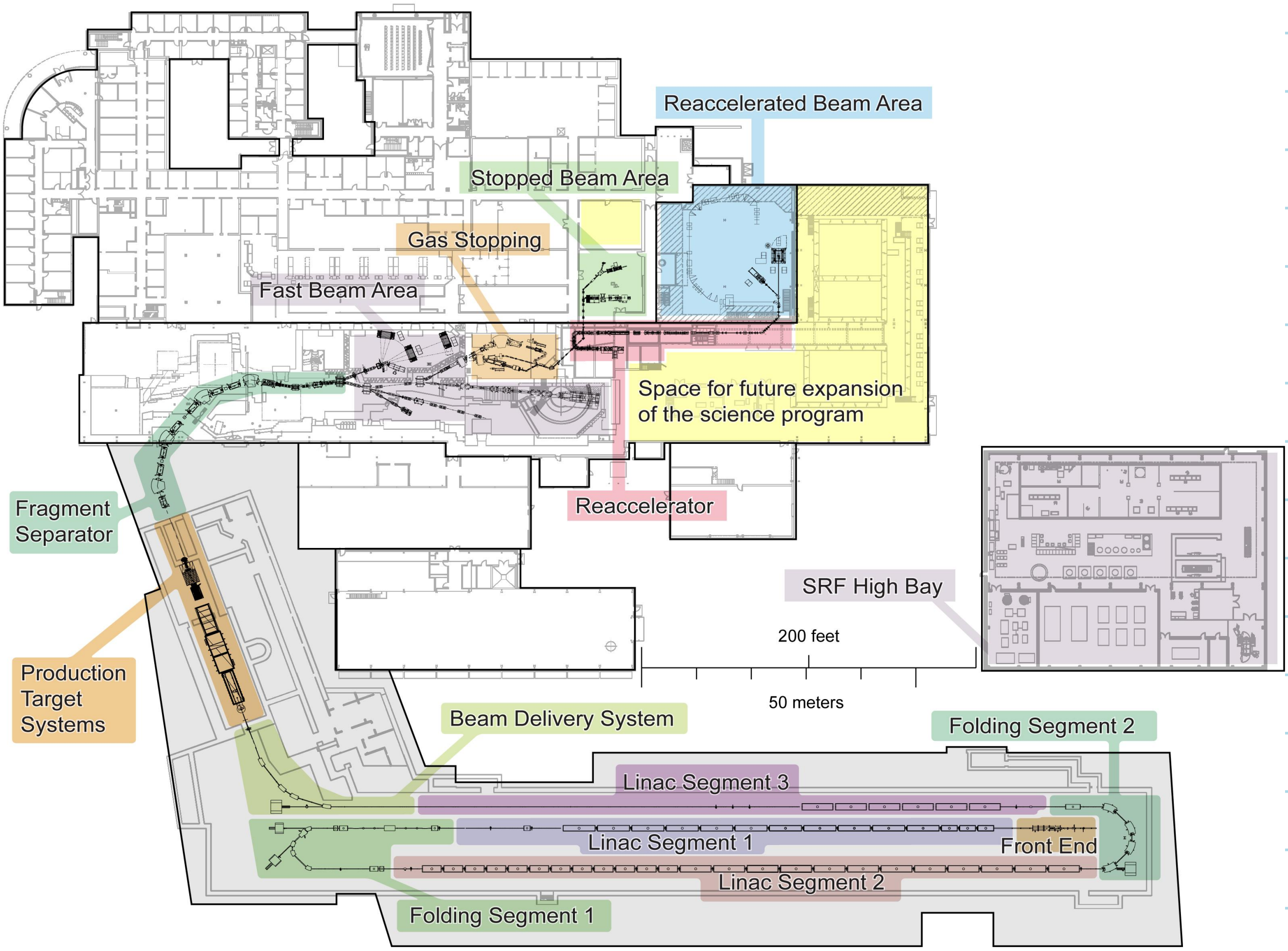
NATL SUPERCONDUCTING CYCLOTRON LABORATORY

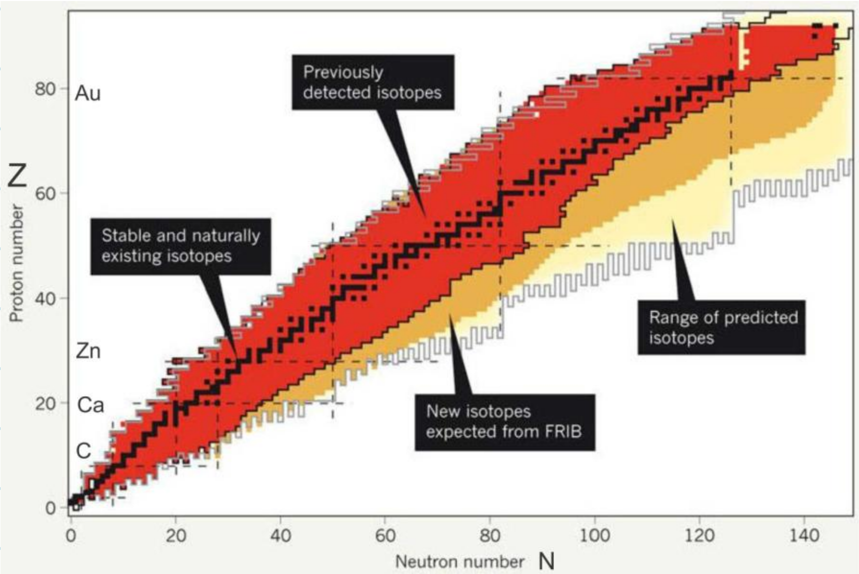


FRIB M$ 730

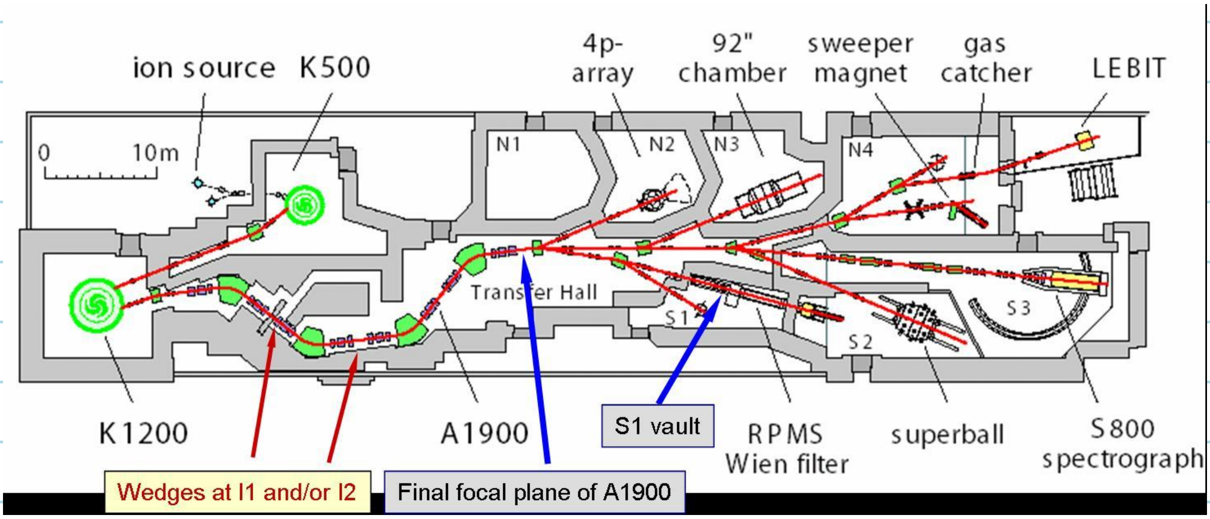
LARGEST INVESTMENT IN LOW-EN NUCL PHYSICS


GROVE
CONNELLY


Reaccelerated Beam Area
Stopped Beam Area
Gas Stopping
Fast Beam Area
Space for future expansion
of the science program
Reaccelerator
Fragment
Separator
Production
Target
Systems
SRF High Bay
200 feet
50 meters
Beam Delivery System
Folding Segment 2
Linac Segment 3
Linac Segment 1
Front End
Linac Segment 2
Folding Segment 1



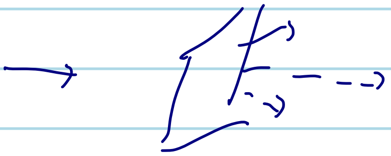
NOMINALLY HEAVY IONS ARE NUCLEI HEAVIER THAN ALPHA

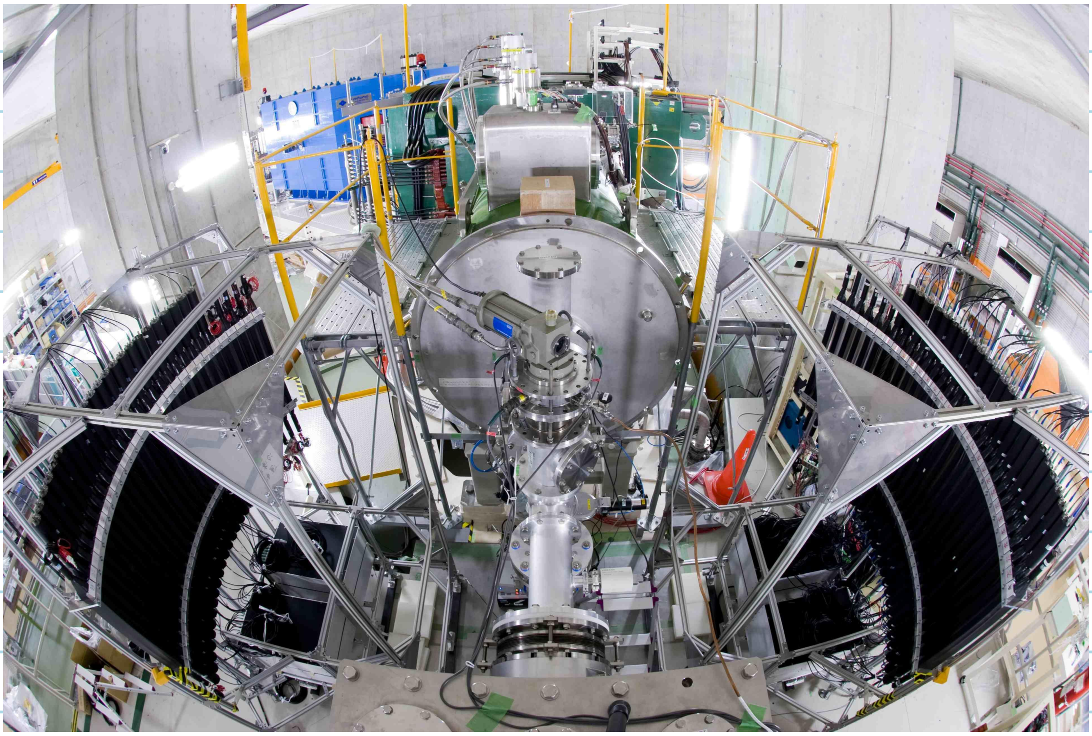


PERIPHERAL COLLISIONS

CENTRAL COLL → EQ. OF STATE

HEAVY PROJECTILES / TARGETS





BEAM ENERGIES IN MeV/nucl ← PER NUCLEON

NUCLEON MASSES $m_p = 938.3\,\mathrm{MeV}/c^2$

$m_n = 939.6\,\mathrm{MeV}/c^2$

ENERGIES FOR GOS

$\sim 100\,\mathrm{MeV/nucl} - 10\,\mathrm{GeV/nucl}$

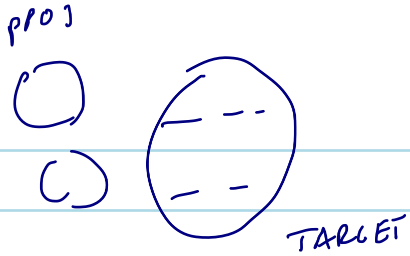
$\lesssim 2\,\mathrm{GeV/nucl}$

RELATIVISTIC OR NOT !

NONRELATIVISTICALLY

TYPICALLY SYMMETRIC SYSTEMS

$1u = 931.5$ MeV



$$\frac{E_{lab}}{A} = \frac{m_N v_{lab}^2}{2}$$

$$v_{cm} = \frac{v_{lab}}{2}$$

$$\frac{E_{cm}}{A} = \frac{m_N v_{cm}^2}{2} = \frac{m_N}{2}\left(\frac{v_{lab}}{2}\right)^2 = \frac{1}{4}\frac{m_N v_{lab}^2}{2} = \frac{1}{4}\frac{E_{lab}}{A}$$

$\frac{E_{lab}}{A} \sim 1$ GeV/nucl $\frac{E_{cm}}{A} \sim 250$ MeV/nucl

$\gamma = 1.25$

$\sim 25\%$

$\vec{v} = \frac{\vec{p}}{m}$ NONRELATIVISTICALLY

$v \to c$ AS $? \gg m$

$\vec{v}_\perp \to \frac{\vec{p}_\perp}{m} \leftarrow$ $v_\parallel \to$ RAPIDITY y

NONRELATIVISTICALLY $y \simeq \frac{v_\parallel}{c}$

$m_\perp = \sqrt{m^2 + p_\perp^2}$ $\leftarrow$ TRANSVERSE MASS

HALF-WAY TO ENERGY

$$E = \sqrt{m^2 + p^2} = \sqrt{m_\perp^2 + p_\parallel^2}$$

$E^2 = m_\perp^2 + p_\parallel^2$ $\frac{E^2}{m_\perp^2} = 1 + \frac{p_\parallel^2}{m_\perp^2}$

$E = m_\perp \cosh y$ $\cosh^2 y = 1 + \sinh^2 y$

$p_\parallel = m_\perp \sinh y \simeq m y$ $y \simeq p_\parallel / m = v_\parallel$

$$E = \frac{m_\perp}{2}\left(e^{y} + e^{-y}\right) \qquad E + p_{\parallel} = m_\perp e^{y}$$

$$E - p_{\parallel} = m_\perp e^{-y}$$

$$p_{\parallel} = \frac{m_\perp}{2}\left(e^{y} - e^{-y}\right)$$

$$e^{2y} = \frac{E + p_{\parallel}}{E - p_{\parallel}} = \frac{1 + \frac{p_{\parallel}}{E}}{1 - \frac{p_{\parallel}}{E}}$$

$$\frac{p_{\parallel}}{E} = v_{\parallel} \qquad \vec{v} = \frac{\vec{p}}{E}$$

$$e^{2y} = \frac{1 + v_{\parallel}}{1 - v_{\parallel}} \qquad p_{\parallel} = m_\perp \sinh y$$

$$p_{\parallel} \to \pm\infty \qquad y \to \pm\infty$$

LORENTZ TR ALONG BEAM DIRECTION

E.C. LAB → CM LAB → ALAB

$$E' = \gamma E + \beta\gamma p_{\parallel} \qquad p'_{\parallel} = \gamma p_{\parallel} + \gamma\beta E$$

$$e^{2y_\beta} = \frac{1+\beta}{1-\beta}$$

$$e^{2y'} = \frac{E' + p'_{\parallel}}{E' - p'_{\parallel}} = \frac{\gamma E + \beta\gamma p_{\parallel} + \gamma p_{\parallel} + \gamma\beta E}{\gamma E + \beta\gamma p_{\parallel} - \gamma p_{\parallel} - \gamma\beta E}$$

$$= \frac{E(1+\beta) + p_{\parallel}(1+\beta)}{E(1-\beta) - p_{\parallel}(1-\beta)} = \frac{1+\beta}{1-\beta}\,\frac{E + p_{\parallel}}{E - p_{\parallel}}$$

$$= e^{2y_\beta} e^{2y} = e^{2(y + y_\beta)}$$

$$\vec{p}_\perp{}' = \vec{p}_\perp \qquad y' = y + y_\beta$$

LORENTZ TRANSFORMATION , ALONG THE BEAM JUST SHIFTS THE RAPIDITY

REFLECTION $\qquad p_\parallel \to -p_\parallel$

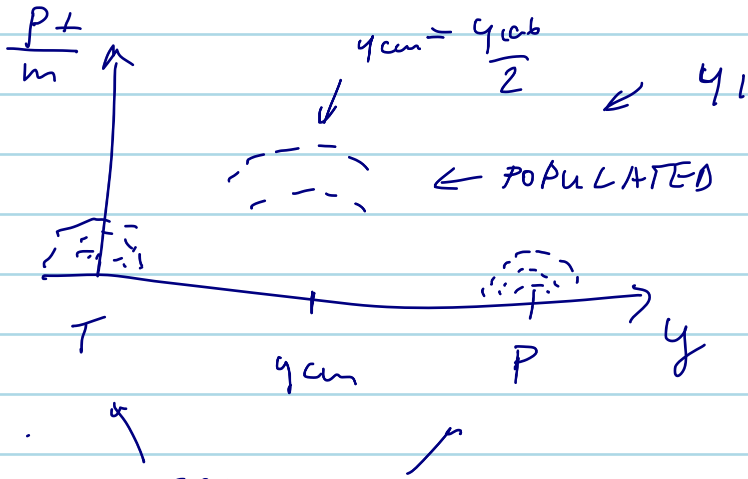
$$e^{2y} = \frac{E+p_\parallel}{E-p_\parallel} \qquad\qquad \frac{E-p_\parallel}{E+p_\parallel} = e^{-2y}$$

$$y \to -y$$

$y \to$ REPLACEMENT OF $v_\parallel$

UNDER GALILEAN TRANSF. $v_\parallel$ SHIFTS

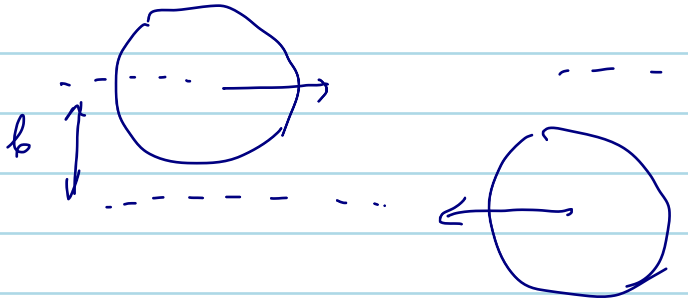
" — LORENTZ — " y — " —



SYMMETRIC COLLISION

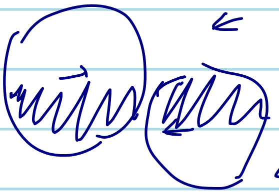
← POPULATED BY PRODUCTS OF REPEATED INTERACTIONS OF PROJECTILE & TARGET NUCLEONS

BREAKUP OF ORIGINAL NUCLEI



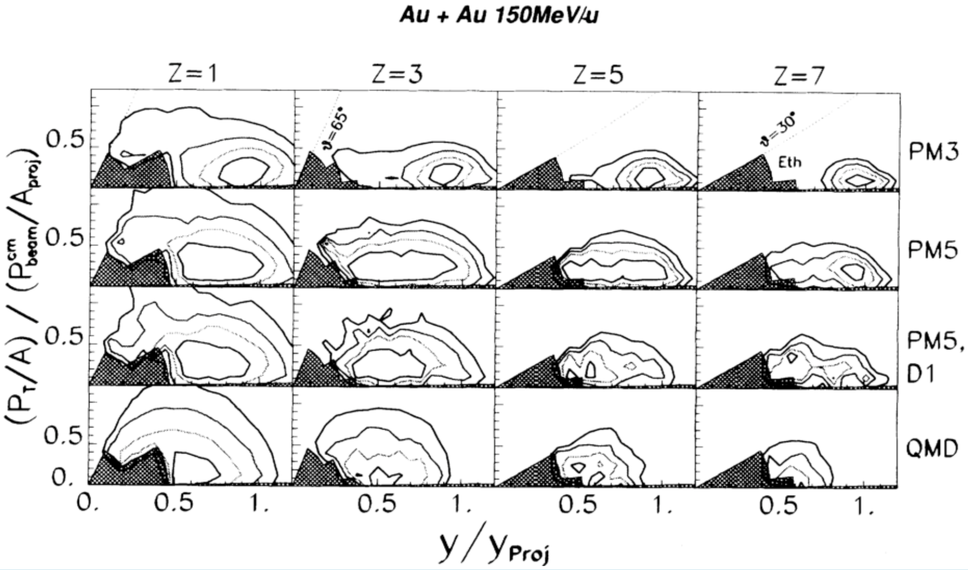
b IMPACT PARAMETER

$$b_{max} \simeq R_T + R_P$$



← PARTICIPANTS — VIOLENT INTERACTION

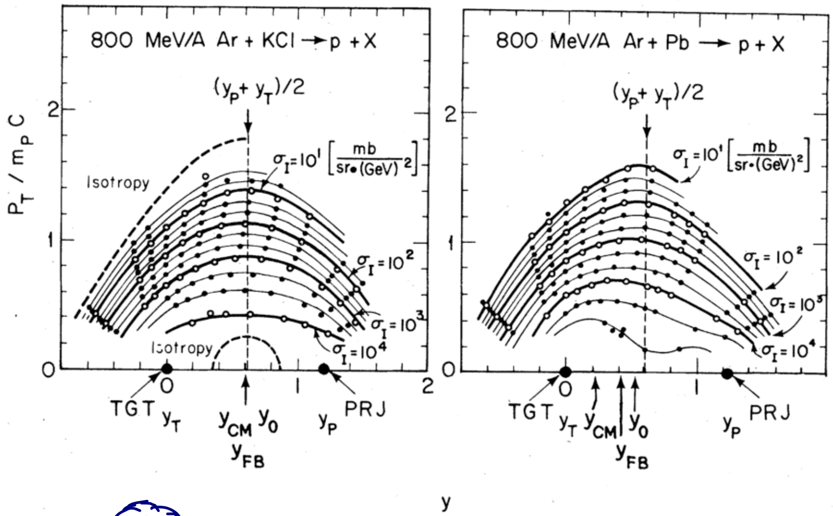
← SPECTATORS — FRAGMENTATION



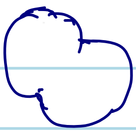
PERIPHERAL

CENTRAL

THEORY



TYPE OF PROCESS



DEEP INELASTIC COLLISIONS

FRAGMENTATION

PARTICIPANT REGION VAPORIZATION

NEW PARTICLE PRODUCTION

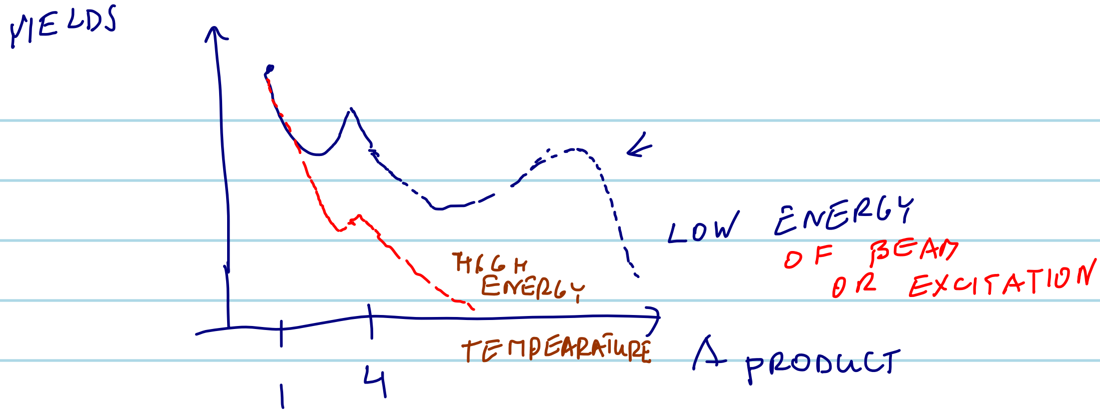
$N+N \leftrightarrow N+\Delta$

$\Delta \leftrightarrow \pi + N$

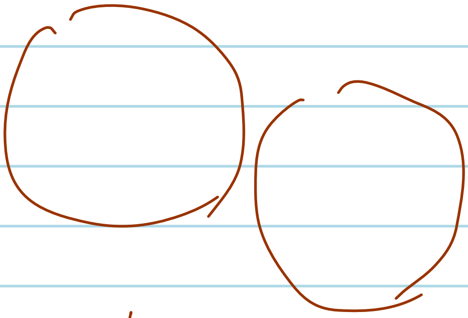
↳ NEW PARTICLES DOMINATE

E_{low}

E_{lab} / nucl



TIMES MEASURED IN fm/c



~10 fm

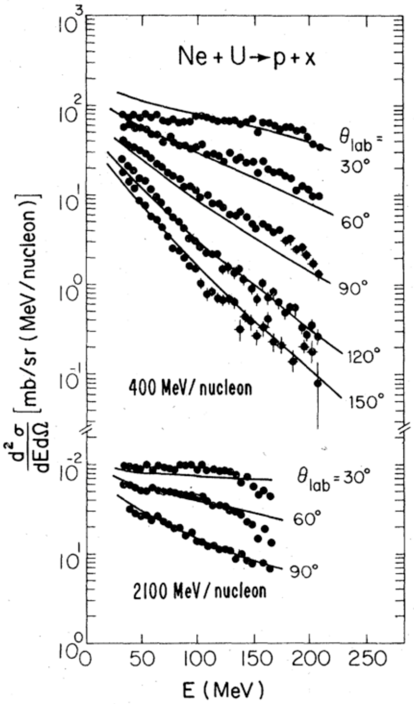
$v_F \sim 0.25\,c$

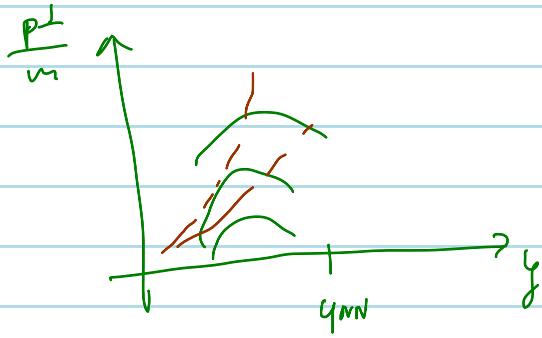
up TO c

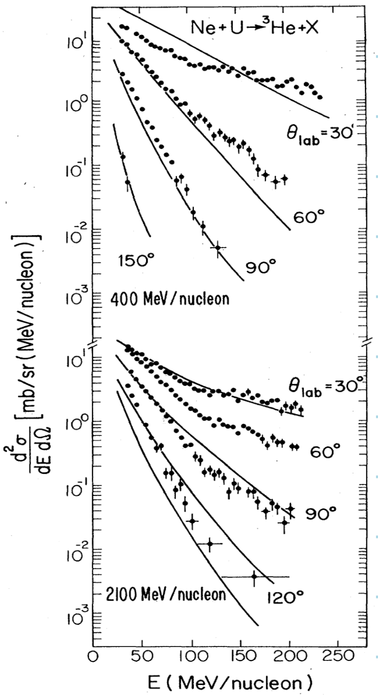
LOW ENERGIES
VIOLENT STAGE
~50 fm/c

THERMAL MODEL
CAN BE APPLIED
FOR PARTICIPANT
& SPECTATOR REGIONS

HIGH ENERGIES
WITH LORENTZ
FACTORS
ABOVE 2 GeV/nucl
~15 fm/c

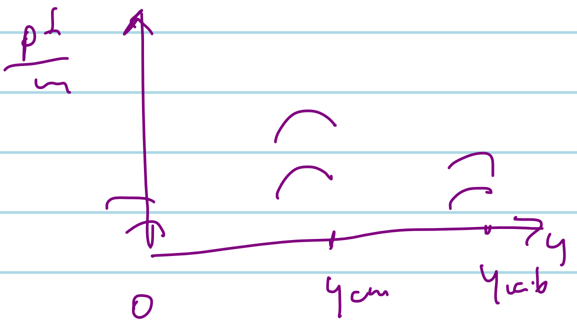






PARTICLE SPECTRA IN THERMAL MODEL

IN THE FRAME OF THE EMITTING SOURCE



VOLUME OF SOURCE

$$\frac{dN_x}{d^3p_x} = \frac{V}{(2\pi)^3}\, g\, e^{\left(\mu_x - \frac{p_x^2}{2m_x} + B_x\right)/T}$$

$g = 2s+1$ STAT FACTOR

CHEM POTENTIAL $\underbrace{\mu_x = N_x \mu_n + Z_x \mu_p}$

$X \leftrightarrow N_x\, n + Z_x\, p$

$$m_x \simeq A_x\, m_N$$

$$\frac{p_x^2}{2m_x} \simeq \frac{p_x^2}{2A_x m_N} = \frac{1}{2m_N}\left(\frac{p_x}{A_x}\right)^2 \frac{A_x^2}{A_x} = \frac{1}{2m_N}\left(\frac{p_x}{A_x}\right)^2 A_x$$

$$e^{\left(\mu_x - \frac{p_x^2}{2m_x}\right)/T} = e^{\left(N_x\mu_n + Z_x\mu_p - (N_x + Z_x)\frac{1}{2m_N}\left(\frac{p_x}{A_x}\right)^2\right)}$$

$$= \left[e^{\left(\mu_n - \frac{1}{2m_N}\left(\frac{p_x}{A_x}\right)^2\right)/T}\right]^{N_x} \left[e^{\left(\mu_p - \frac{1}{2m_N}\left(\frac{p_x}{A_x}\right)^2\right)/T}\right]^{Z_x}$$

$$\frac{dN_x}{d^3p_x} = \frac{V}{(2\pi)^3}\left[\frac{(2\pi)^3}{V}\right]^A \frac{g}{2^A}\, e^{B_x/T} \cdot \left[\frac{dN_n}{d^3(p_x/A)}\right]^{N_x} \left[\frac{dN_p}{d^3(p_x/A)}\right]^{Z_x}$$

SCALING RELATION BETWEEN NUCLEON & FRAGMENT SPECTRA

POTENTIAL BENEFITS:

→ NEUTRON SPECTRUM THAT COULD NOT BE DIRECTLY MEASURED

→ VOLUME OF EMITTING SOURCE V

→ VELOCITY OF EMITTING SOURCE SINCE DIVISION p_x/A_x DONE IN FRAME OF EMITTING SOURCE