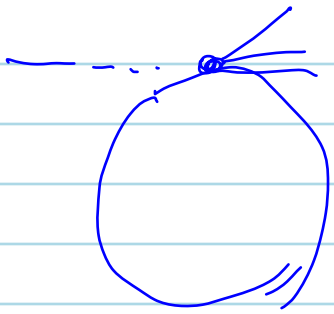
PERIPHERAL

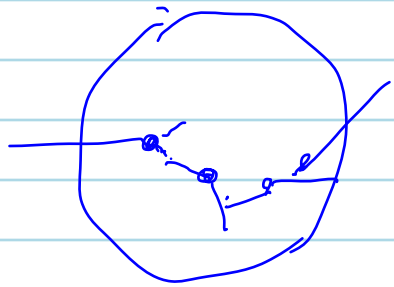


EXCLUSIVE

PRODUCTS
UNSCATHED

$\sigma \propto A^{2/3}$

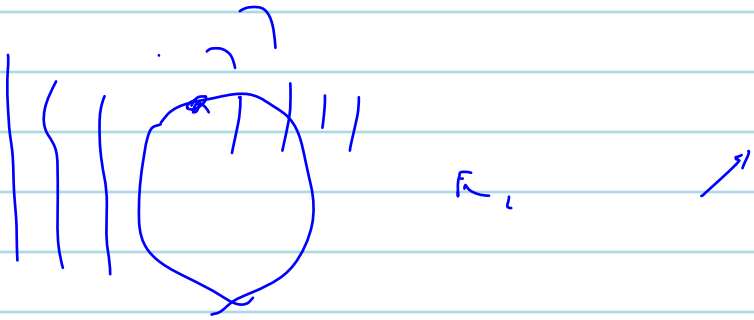
SEMICENTRAL
CENTRAL



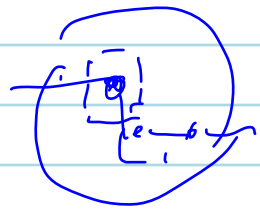
INCLUSIVE

$\sigma \propto A$

ENERGY REPRESENTATION



PROBABILITY $\propto$ |AMPLITUDE|^2



EVOLUTION
OF PROBABILITY
IN SPACE
-TIME
REPRESENTATION

$\vec{r}, \vec{p}$ AT t

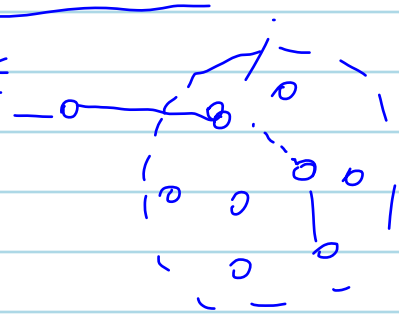
DE-BROGLIE
WAVELENGTH
SHORT & INT RANGE

TRANSPORT
THEORY

NUCLEAR TRANSPORT MODELS

- CASCADE
- BUU
- QMD

CASCADE



FERMI MOMENTA

NUCLEONS MOVE ON STRAIGHT LINES

? NO PAULI SUPPRESSION

- SIMPLE
- DISADVANTAGES
  INCONSISTENT
  NUCLEUS FALLS

BUU : BOLTZMAN - UHLENBECK - WEHLING MODEL

PHASE SPACE OCCUPATION FUNCTIONS

$$f(\bar{r}, \bar{p}, t)$$

$$N_{\Delta p \Delta r} = \int_{\substack{\Delta p \\ \Delta r}} \frac{f \, d^3p \, d^3p}{(2\pi\hbar)^3}$$

$$\frac{\partial f(\bar{r}\,\bar{p}\,t)}{\partial t} + \underbrace{\frac{\partial \varepsilon(\bar{r}\,\bar{p}\,t)}{\partial \bar{p}}}_{\text{VELOCITY}} \frac{\partial f}{\partial \bar{r}} - \underbrace{\frac{\partial \varepsilon(\bar{r}\,\bar{p}\,t)}{\partial \bar{r}}}_{\text{FORCE}} \frac{\partial f}{\partial \bar{p}} = \underset{\substack{\uparrow \\ \text{COLLISION} \\ \text{INTEGRAL}}}{I}$$

ε - 1-PTCLE ENERGIE

$$E = E\{f\}$$

$$\varepsilon = \frac{\delta E}{\delta f}$$

$$\frac{d}{dt} f(\bar{r}(t), \bar{p}(t), t) = I \qquad I = 0 \qquad f = \text{const}$$

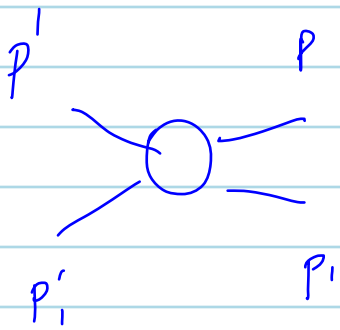
$$\frac{d\bar{r}}{dt} = \frac{\partial \varepsilon}{\partial p} \qquad \frac{d\bar{p}}{dt} = -\frac{\partial \varepsilon}{\partial \bar{r}}$$

$$I(\bar{r}\,\bar{p}\,t) = \int \frac{d^3 p_1}{(2\pi\hbar)^3} \Big[(1-f)(1-f_1) f(p_1') f(p') - f f_1 (1-f_1')(1-f') \Big]$$

FEEDING TERM DEPLETION

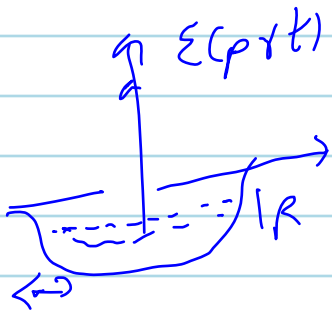
$$\int \frac{d^3 p_1'}{(2\pi\hbar)^3} \frac{d^3 p'}{(2\pi\hbar)^3} \qquad |\mathcal{M}_{p_1' p' \to p p_1}|^2$$

$$(2\pi\hbar)^3 \delta(p + p_1 - p - p_1') \, \delta(\varepsilon_p + \varepsilon_{p_1} - \varepsilon_p - \varepsilon_{p_1'})$$



$\longrightarrow$ TIME $\longleftarrow$ BACKWARD

IN THE GROUND STATE $I = 0$



OTHER ADVANTAGE

$E = E\{f\}$

RELATIVISTIC EXTENSION
STRAIGHTFORWARD
CAUSALITY FINE

BUU - TF F/G.

DISADVANTAGES: CASCADE : A-BODY THEORY

BUU - ONE-BODY THEORY

COMPROMISE : QMD

QUANTUM MOLECULAR DYNAMICS

$i = 1, .. A$ NUCLEONS

$$\frac{d\bar{r}_i}{dt} = \{\bar{r}_i, \mathcal{H}\} \qquad \frac{dp_i}{dt} = \{p_i, \mathcal{H}\} + \left(\frac{dp_i}{dt}\right)_I$$

$$\mathcal{H}(\{r\}\{p\}, t)$$

TAKEN FROM BUU

$\mathcal{H} \leftrightarrow E$ IN BUU

A-BODY CORRELATIONS
ADVANCED IN TIME

- RELATIVISTIC FORMULATION
CAUSALITY

STABILITY OF GROUND STATE NUCLEI

$N: n, p$ $\quad \pi \quad \Delta \quad N^* \rightarrow$ 2 GeV RESONANCES IN MASS

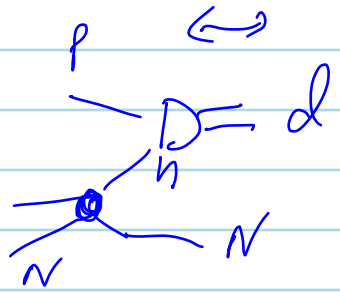
$\pi + N \rightarrow \Delta \rightarrow \pi + N$

5 REABSORPTIONS / EMISSIONS

CLUSTERS $d, t\ {}^3He, \alpha$

BUU GENERALLY DOES NOT DESCRIBE THEM
CASCADE NEITHER

FEW BODY COLLISIONS



? CONNECTION TO MICROSCOPIC THEORY?

EXCLUSIVE PROCESS

$[(0|aa] \rightarrow \ldots \quad (a^+a^+|0)$ VACUUM

$t = +\infty$ $\quad$ DRESS $\quad$ $t = -\infty$

$t \rightarrow$ BACKWARD $\quad$ $\leftarrow t$ FORWARD DRESSING

FEYNMAN DIAGRAMS $\quad \int_{-\infty}^{\infty} dt$

INCLUSIVE

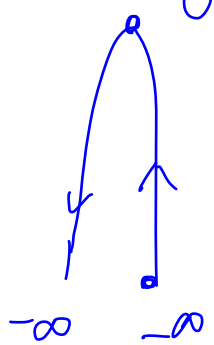
$$\left(\langle GS| \right) \quad \hat{O} \left(|GS\rangle \right)$$

$\rightarrow$ $\leftarrow$ FORWARD

EXPECTATION VALUE

$$\int_{-\infty}^{-\infty} dt$$

$\hat{O}(t)$



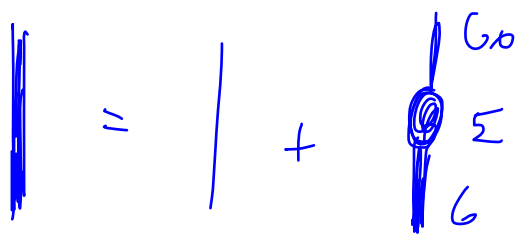
$-\infty$ $-\infty$

$|GS\rangle$

ANYTHING POSSIBLE

FEYNMAN DIAGRAMS

DYSON EQ



$$G = G_0 + G_0 \Sigma G$$

G G_0

COUPLING OF THE PTCLE W/ SURROUNDING

GIBUU _ GIESSEN BUU