Nonequilibrium IMFs:

Cluster Formation on a Fast Time Scale

(see IUCLF experiment CEB1)

200-500 MeV p + 197Au → IMFs

? 200 MeV/A Sn + H ?
FIG. 7. Energy spectra of $^5$Be fragments from 300 MeV proton interactions with Ag measured at three laboratory angles. The solid curves are the total two-component calculation discussed in the text, and the dashed curves are the evaporative component of this calculation.
Open questions

- C fragments at backward angles have a thermal-like spectral shape: \( T \approx 3 \text{ MeV} \).

- At forward angles:
  → Break in the curve: \( T_S \approx 8-10 \text{ MeV} \) (x3 the thermal-like C).
  → Very fast moving, extending up to \( 2xP_{\text{beam}} \approx 60 \text{ MeV} \) and above.
  → Yield of high momentum component increases as \( \Theta_{\text{lab}} \) decreases.

- Yield of nonequilibrium cluster increases with increasing beam momentum.

What process(es) is (are) responsible for the emission of these fast clusters?

QMD Tests (Aicheler, Horiuchi)

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Which Mechanism?

- Hot spot (small number of participants, $A \approx 25$)
  
  Forward fast moving nonequilibrium cluster
  $\rightarrow$ Small source for the fast particles/clusters.
  $\rightarrow$ High temperature.
  $\rightarrow$ Diluted systems (nuclear periphery, T).
  $\rightarrow$ Neutron rich systems (nuclear periphery).

  Backward equilibrium clusters
  $\rightarrow$ Large source for thermal-like fragments.
  $\rightarrow$ Low temperature.

- Cold "knock-out"

  Used by Fujita (PRL 39, 174 (1977)) to explain the high energy proton cross-sections near $180^\circ$.
  $\rightarrow$ Cluster pre-exist at the nuclear periphery.
  $\rightarrow$ Diluted systems.
  $\rightarrow$ Neutron Rich.

Forward-backward momentum correlation

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sitivity to the size e investigate two-ions as functions and compare these i performed with suggests a natural energetic protons sity Ag/cm² Ag target Coincident light solute hodoscope pes [16]. Four of four silicon detect- cly position information detectors were ntended to higher NaI(Tl) detectors ion from the 5-mm protons produced re target by 200-performed with the θ° in the laborato- ions are shown in t, the spectra are brated or nearly er energies, none, with some con- higher-energy ith increasing an- on function $R(q)$ 3d $Y_{12}(p_1, p_2)$ and

FIG. 2. (a) p-p correlation functions measured for the $^3$He+Ag reactions at 200 MeV. The energy gates and angular locations of the center of the hodoscope are indicated in the figure. The curves are discussed in the text. (b) Comparison of experimental p-p correlation functions with predictions of the BUU theory for the $^3$He+Ag reaction at 200 MeV. The dotted curve is discussed in the text.


eergy gates containing different portions of equilibrium and nonequilibrium emission. Consistent with previous measurements [4,6-15], the correlation functions exhibit maxima at $q = 20$ MeV/c due to the attractive singlet S-
dashed and dot-dashed curves show calculations for Gaussian sources of negligible lifetime,

\[ g(p,r,t) \propto \rho_0 \left( e^{-r^2/r_0^2} \right) \delta(t) \]  

(5)

with the specific source radii \( r_0 \) given in the figure. The calculations illustrate that the correlation functions for the most energetic protons are consistent with instantaneous emission by a system significantly smaller than the target nucleus.

Further insight can be obtained from the comparison, in Fig. 3, of the Gaussian source radii extracted from this experiment and, therefore, it is import-averaged correlation functions. They are based on the Boltzmann transport equation and reflect the energy protons sensitive to emission. Indeed, source radii for these protons are observed in the microscopic dynamic correlation functions to satisfy the Boltzmann equation [1]. The consistent mean field, using Pauli exclusion principles of clusters, nucleon-nucleon interactions, and a compressing Refs. [5] are valid in the context of the commercial procedure.

The nucleon density predicted by the first-order term in the dashed, dot-dashed correlation function, nonequilibrium is intermediate \( E_p \) energy gate the predictions of the systematic expectation for the spin correlation.
$\Theta_p = 16^\circ$

$^3\text{He} + ^{238}\text{U} \rightarrow \gamma\gamma - \gamma\gamma - \text{DMF Coincidence}$

$\langle \text{LMT} \rangle \sim 0.8$

\[
\begin{align*}
T_{\text{RES}} &= 7.2 \text{ MeV} \\
T_{\text{CN}} &= 3.0
\end{align*}
\]

$\langle \text{LMT} \rangle \sim 0.95$

\[
\begin{align*}
T_{\text{RES}} &= 6.6 \text{ MeV} \\
T_{\text{CN}} &= 2.6
\end{align*}
\]

$\langle \text{LMT} \rangle \sim 1.0$

\[
\begin{align*}
T_{\text{RES}} &= 6.1 \text{ MeV} \\
T_{\text{CN}} &= 2.1
\end{align*}
\]

$\langle \text{LMT} \rangle \sim 1.0$

\[
\begin{align*}
T_{\text{RES}} &= 4.0 \text{ MeV} \\
T_{\text{CN}} &= 1.5
\end{align*}
\]

Fatemi et al., PRC

• NEQ: enhanced production of n-deficient isotopes
Temperature Guages


slope parameter
p,d,t,α,…

\[ \ln(\frac{dY}{dE}) = e^{-E/T} \]

isotopic composition
\[ \frac{(^3\text{He}/^4\text{He})}{(^6\text{Li}/^7\text{Li})} \]

\[ \ln \frac{Y_1/Y_2}{Y_3/Y_4} \approx (\Delta B_{12} - \Delta B_{34})/T \]

internal excitation
\[ ^5\text{Li}_{16.66} \rightarrow ^5\text{Li}_{gs} \]

\[ N_{16.6} \sim e^{-\Delta E/T} \]

\[ q^2(\text{MeV}/c) \]

200MeV ^3\text{He} + ^7\text{Li} \rightarrow 2\pi + X

E_r = 15-35MeV
E_x = 30-110MeV
\theta_{cm} = 42^\circ

E_{lab} = 20MeV

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Experiment II

**Measured quantities**

- Charge distributions for $Z \leq 15$.

- Mass distributions for $Z \leq 8$.
  \(\sigma \geq 200\text{nb}\)

- Kinetic energy distributions from 2-4 $\leq E/A \leq 140$ MeV for all $Z,A$ and $E/A \leq 400-500$ MeV for protons.

- Small-Angle correlations

- Coincidences:
  - forward-forward.
  - forward-backward.

**Deduced quantities**

- $N/Z$ ratio of nonequilibrium cluster vs equilibrium cluster.

- Temperatures:
  - Slopes of kinetic energy spectra.
  - Population ratio of excited states of light clusters.
  - double-isotope ratio.

- Space-time characteristics from p-p correlations (HBT):
  - Source sizes.
  - Emission time scale.

- Reaction Dynamics:
  - Forward-backward momentum correlation.

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