Determination of freeze-out temperatures

Exited state populations:

\[
\begin{align*}
\text{20.1 MeV} & \quad ^4\text{He} \\
\text{0.0 MeV} & \quad p^+ ^3\text{H} \\
\end{align*}
\]

\[\alpha_{\text{g.s.}}\]

\[
\frac{P_1}{P_2} = \frac{2J_1 + 1}{2J_2 + 1} \exp\left(-\frac{\Delta E^*}{T_{\text{App}}}\right)
\]

Isotope double ratios:

\[
\begin{align*}
\frac{Y_1(Z, A_j)}{Y_2(Z, A_j + 1)} & = a \cdot \exp\left(\frac{B_1 - B_2 - B_3 + B_4}{T_{\text{App}}}\right) \\
\frac{Y_3(Z, A_j)}{Y_4(Z, A_j + 1)} & = a \cdot \exp\left(\frac{B_1 - B_2 - B_3 + B_4}{T_{\text{App}}}\right)
\end{align*}
\]

Au+Au, E/A = 35 MeV
Central collisions

\[T_{\text{em}} = 4.2 \pm 0.6 \text{ MeV}\]

\[T_{\text{em}} = 4.4 \pm 0.2 \text{ MeV}\]

\[\hat{b} < 0.45\]

- **Excellent consistency with thermal equilibrium for central collisions near the multi-fragmentation threshold**
- **Deduced temperatures are close to SMM+MSU decay predictions.**

\[PRL, 78, 1648 (1997)\]
Comparison of He excited state $T(^4\text{He}^*)$ and isotope ratio $T_{\text{iso}}(\text{He})$

Sequential decays should affect $T(^4\text{He}^*)$ and $T_{\text{iso}}(\text{He})$ the same

Experimentally, $T(^4\text{He}^*)$ behaves very differently than $T_{\text{iso}}(\text{He})$. 
Grand canonical temperature vs. canonical temperature

\[ \frac{\langle n_{k+1,k}\rangle}{\langle n_{k,k+1}\rangle} \]

\[ T_{\text{actual}} = 5 \text{ MeV} \]
\[ T_{\text{best fit}} = 3.4 \text{ MeV} \]

\[ \Delta E_B \text{ (MeV)} \]

- **Exact canonical**
- **Eq. 2.10**
Summary– How well can we measure temperature

Q: What is temperature

A: Due to lack of consistency in temperature measurements at high energy (E/A > 40 MeV), temperature can be measured well only in systems with low excitation (E/A < 35 MeV, T ~ 4 MeV). Reality constraints including sequential decays may put a limit on the temperature measurement.

Ar+Sc, Kr+Ni E/A=35-150 MeV, PRC, 58, 2636 (1998)
MSU Sequential decay calc, PLB, 431, 8 (1998)
Grand canonical and canonical calculations, PRC, 64, 044608 (2001)
Summary

Q: What is equilibrium?

Q: How far from equilibrium are the reactions?

Q: How can one determine kinetic, chemical or isospin equilibrium?

Q: What is the meaning of temperature?

Q: What values of temperatures are observed or calculated?

Systems studied:
Models used in the calc’s: