Dynamical emission and isotope thermometry

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Ratios of the populations of ground and excited states of 3He, 5Li, and 4Be and double ratios constructed from the yields 3He, 5Li, and 4Be and double ratios constructed from the yields 3He, 5Li, and 4Be nuclei and from thermometers based upon the yields of carbon isotopes. In contrast, apparent temperatures obtained from thermometers based upon the ratios using helium isotopes increase monotonically with incident energy.

One of the general expectations for a system undergoing a first-order phase transition is an enhanced heat capacity at temperatures of the order 4–6 MeV latent heat required to transform from one phase to the other. A first-order phase transition is an enhanced heat capacity at temperatures obtained from thermometers based upon the ratios using helium isotopes increase monotonically with incident energy.

The ratios of populations of ground and excited states of 4He, 5Li, and 8Be nuclei and from thermometers based upon the yields of carbon isotopes. In contrast, apparent temperatures obtained from thermometers based upon the ratios using helium isotopes increase monotonically with incident energy. [S0556-2813(98)50511-0]

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\begin{equation}
R_{\text{iso}} = \frac{Y(A_1,Z_1)/Y(A_1+1,Z_1)}{Y(A_2,Z_2)/Y(A_2+1,Z_2)} = \frac{1}{a} \exp(B/T),
\end{equation}

where $Y(A_i,Z_i)$ is the yield for isotope with mass $A_i$ and charge $Z_i$; $a$ is a statistical factor determined by spin values and kinematics factors; $B = E_B(A_1,Z_1) - E_B(A_1+1,Z_1) - E_B(A_2,Z_2) + E_B(A_2+1,Z_2)$; and $E_B(A_i,Z_i)$ is the binding energy of the $i$th nucleus. Such double yield ratios have the advantage of being insensitive to chemical potential terms which strongly influence the fragment isotopic distributions.

Similarly, the ratios $R_{ij}$ of the yields of states $i$ and $j$ of a specific fragment, prior to the secondary decay of the excited fragments, are given by [25]

\begin{equation}
R_{ij} = \frac{Y_i}{Y_j} = \frac{(2J_i+1)}{(2J_j+1)} e^{-(E_i^* - E_j^*)/T},
\end{equation}

where $Y_i$ is the yield, $E_i^*$ is the excitation energy, and $J_i$ is the spin of the state $i$. In the context of rate equation approaches [26], instantaneous particle emission rates depend upon instantaneous temperatures in ways analogous to Eqs. (1) and (2); however, the total yields reflect an averaging over the time dependent cooling of the system [27–29].

"Apparent" temperatures obtained from Eqs. (1) or (2), often require corrections for the secondary decay of excited fragments. The exact magnitude of such corrections depends on the isotope or excited state ratio and the temperature [7,11,13,14]. These corrections can be minimized by choosing ratios characterized by large binding energy differences $B$ in Eq. (1) or large $\Delta E = E_i^* - E_j^*$ in Eq. (2) (i.e., $B$, $\Delta E \gg T$).
Consistent values of $T_{\text{iso}}$ and $T_{\Delta E}$ for large $B$ and $\Delta E$, respectively, have been obtained for central Au+Au collisions at incident energies $35$ MeV $\leq$ $E/A$ $\leq$ $50$ MeV [7,12]. For $E/A$ $>$ $50$ MeV, however, temperatures from the two methods diverge: values for $T_{\text{iso}}(\text{He})$ extracted from Eq. (1) using yields of $^3\text{He}$ and $^4\text{He}$ isotopes increase with incident energy, but values for $T_{\Delta E}$ extracted from Eq. (2) using yields of highly excited states of $^4\text{He}$, $^5\text{Li}$, and $^6\text{Be}$ nuclei do not [12]. This discrepancy has been argued to be the result of a suppression of the numbers of highly excited fragments within the disintegrating nuclear medium [14] which would lower the values of $T_{\Delta E}$ extracted via Eq. (2). Alternatively, early emission of $^3\text{He}$ [27,29] could elevate the $^3\text{He}$/$^4\text{He}$ isotopic ratio and raise the values of $T_{\text{iso}}(\text{He})$ extracted via Eq. (1). In this paper, we determine $T_{\text{iso}}$ and $T_{\Delta E}$ for central Kr+Nb collisions at $E/A$ $=$ $35$, $70$, $100$, and $120$ MeV. Values of $T_{\text{iso}}$ are extracted both from $Y(^3\text{He})/Y(^4\text{He})$ and from $Y(^{12}\text{C})/Y(^{12}\text{C})$ ratios—both of which have large $B$ values [6,13]. Consistent with the findings for Au+Au collisions, $T_{\text{iso}}(\text{He})$ and $T_{\Delta E}$ agree at low energies ($E/A$ $=$ $35$ MeV) but disagree at higher energies. Surprisingly, our results show that $T_{\text{iso}}(\text{C})$ from carbon isotopes agree with $T_{\Delta E}$ from excited states. Thus, nonstatistical $^3\text{He}$ emission may be a more likely explanation of the discrepancy between $T_{\text{iso}}(\text{He})$ and $T_{\Delta E}$ values than the suppression of excited fragments within the disintegrating nuclear medium.

The experiment was performed by bombarding $^{93}\text{Nb}$ targets of $6$ and $20$ mg/cm$^2$ areal density with $^{86}\text{Kr}$ beams at $E/A$ $=$ $35$, $70$, $100$, $120$ MeV from the National Superconducting Cyclotron Laboratory at Michigan State University (MSU). Impact parameters were selected by gates on the multiplicity of identified charged particles detected at polar angles of $\theta_{\text{lab}}$ $=$ $7^\circ$–$157^\circ$ using $215$ plastic $\Delta E$–$E$ phoswich detectors of the MSU 4$\pi$ array. The data presented here represent central collisions with a charged particle multiplicity selection on the MSU 4$\pi$ array corresponding to the top $20\%$ of the total cross section and reduced impact parameter $b/b_{\text{max}}$ $\leq$ $0.45$.

Two hexagonal modules of the 4$\pi$ array, located at $\theta_{\text{lab}}$ $=$ $37^\circ$ and $79^\circ$ were replaced by a $96$-telescope hodoscope (HODO-CT) that covered approximate polar and azimuthal angular ranges of $43^\circ$ and $40^\circ$, respectively, in the laboratory. Each of these telescopes subtended a solid angle of $1.83$ msr and consisted of a $300$-$\mu$m-thick silicon detector followed by a $6$-cm-thick CsI(52) scintillation detector. The centers of neighboring telescopes were separated by relative angles of $3.3^\circ$. To provide good coverage for light charged particles emitted at center-of-mass angles of $\theta_{\text{c.m.}}$ $=$ $90^\circ$, where contributions from the decay of projectilelike and targetlike fragments are minimal, the central angle of the hodoscope was placed at $58^\circ$, $50.6^\circ$, $42.7^\circ$, and $42.7^\circ$ at incident energies of $E/A$ $=$ $35$, $70$, $100$ and $120$ MeV, respectively. In addition, isotopically resolved fragments with $3$ $\leq$ $Z$ $\leq$ $6$ were detected with four heavy-ion telescopes constructed of planar $75$ and $5000$-$\mu$m-thick silicon detectors located at polar angles of $\theta$ $=$ $27^\circ$, $36^\circ$, $75^\circ$, and $84^\circ$. The silicon detectors were calibrated to an accuracy of $2\%$ with a precision pulser and alpha particles emitted from a $^{238}\text{Th}$ source. The CsI(52) scintillators were calibrated to an accuracy of $3\%$ with recoil protons elastically scattered from a CH$_2$ target by $^{86}\text{Kr}$ ions at $E/A$ $=$ $35$ MeV and $^4\text{He}$ ions at $E/A$ $=$ $22$ and $40$ MeV.

Figure 1 demonstrates the isotopic resolution achieved for elements up to carbon with the four heavy-ion telescopes. The relative populations of widely separated states in emitted $^4\text{He}$ ($J_f^\pi$ $=$ $0^+\frac12$, $E^*$ $=$ $20.1$ MeV; $J_f^\pi$ $=$ $0^+\frac12$, g.s.), $^5\text{Li}$ ($J_f^\pi$ $=$ $3/2^+$, $E^*$ $=$ $16.7$ MeV; $J_f^\pi$ $=$ $3/2^+$, g.s.), and $^6\text{Be}$ ($J_f^\pi$ $=$ $1^+$, $E^*$ $=$ $17.6$ MeV; $J_f^\pi$ $=$ $2^+$, $E^*$ $=$ $3$ MeV) fragments were measured with the $96$ element hodoscope. Five of these six states are particle unstable; their populations were measured by detecting the coincident decay products. In Fig. 2, we present data at $E/A$ $=$ $100$ MeV for the decay of particle unstable $^5\text{Li}$ nuclei in the form of correlation functions, $R(E_{\text{rel}})$, which are defined in terms of the measured coincidence yield $Y_{12}(p_1,p_2)$ and the singles yield $Y_1(p_1)$ and $Y_2(p_2)$ as follows:

![Diagram](image-url)
experimental uncertainties primarily reflect uncertainties in the subtraction of the nonresonant background. The extracted temperatures $T_{\Delta E}$ are of the order of 4–4.5 MeV and show a weak variation with incident energy, a trend also observed for central Au+Au collisions [7,12].

Values of $T_{\text{iso}}$ were obtained via Eq. (1) at the four incident energies. Carbon isotope yields were measured with the heavy-ion telescopes while the isotope yield ratios for lighter particles (Z<6) were obtained with selected detectors in the hodoscope situated at $\theta_{\text{c.m.}} \approx 90^\circ \pm 10^\circ$. (Over the measured angular range, all the single isotope yield ratios are relatively constant with respect to scattering angle.) The experimental uncertainties in these ratios mainly reflected the uncertainties in the particle identification (up to 10% in $^{11}$C). Values for $T_{\text{iso}}$(C-Li) (open circles) obtained from ($^{6,7}$Li, $^{11,12}$C) isotope ratios vary little with incident energy, similar to the trends exhibited by the temperatures $T_{\Delta E}(^{7}$Li), $T_{\Delta E}(^{4}$He), and $T_{\Delta E}(^{8}$Be) extracted from excited states populations. Values of $T_{\text{iso}}$ extracted from other possible ratios based upon the large binding energy difference of ($^{11}$C, $^{12}$C) isotopes, including those obtained from ($^{12,13}$C, $^{11,12}$C), follow the same behavior as $T_{\text{iso}}$(C-Li). In contrast, values of $T_{\text{iso}}$(He-Li) (open diamonds) obtained from ($^{6,7}$Li, $^{3,4}$He) isotopes increase monotonically with incident or excitation energy, consistent with trends recently reported for other systems [5,9,12]. Similarly increasing trends are extracted from other possible ratios based upon the large binding energy difference between $^3$He and $^4$He isotopes.

Some corrections to the measured apparent temperatures can be expected due to the secondary decay of heavier isotopes that feed the yields used in Eqs. (1) and (2) [7,13,14]. Secondary decay calculations, however, predict the secondary decay corrections to $T_{\Delta E}(^{7}$Li), $T_{\Delta E}(^{4}$He), $T_{\Delta E}(^{8}$Be), and $T_{\text{iso}}$(He-Li) to be relatively small for apparent temperatures of the order of 4 to 4.5 MeV [7]; thus the predicted corrections to the observed values of $T_{\Delta E}(^{7}$Li), $T_{\Delta E}(^{4}$He), and $T_{\Delta E}(^{8}$Be) are small. Moreover, the secondary decay corrections to $T_{\Delta E}(^{4}$He) and $T_{\text{iso}}$(He-Li) should be nearly identical at all source temperatures because $B$ and $\Delta E$ are comparable and because both are affected primarily by the feeding contributions to the ground state yield of $^4$He [30]. The observed strong discrepancy between $T_{\Delta E}(^{4}$He) and $T_{\text{iso}}$(He-Li) therefore cannot be reconciled by secondary decay calculations. To avoid drawing attention away from this discrepancy, we refer the reader to Refs. [28,20] for discussions of the small secondary decay corrections to $T_{\Delta E}(^{7}$Li), $T_{\Delta E}(^{4}$He) and $T_{\Delta E}(^{8}$Be), and focus here instead upon other issues that may influence the measured quantities more strongly.

For example, the use in Eqs. (1) and (2) of measured binding and excited state energies, with the neglect of a dependence on the volume of the emitted particle, however, is a low density approximation [4,14,31]. In Ref. [14], high values for $T_{\text{iso}}$(He-Li) and low values for $T_{\Delta E}(^{7}$Li) have been predicted within a common statistical framework by assuming that the radii of the unstable $T_{\Delta E}(^{7}$Li) nuclei are equal to the sum of radii of their decay products [32] whereby excited $^5$Li* nuclei are 3.1 times larger in volume than that of ground state $^5$Li nuclei. The yield of excited $^5$Li* then becomes suppressed relative to the yield of the ground state $^5$Li, and $T_{\Delta E}(^{7}$Li) is consequently reduced due

![Graph](image-url)
to the constraint that the size of excited $^5\text{Li}^*$ nuclei imposes upon the size of the remaining system. In contrast, the
volume of $^3\text{He}$ ($17.6\text{ MeV}$) is 0.95 times the volume of $^3\text{Be}$ ($3\text{ MeV}$); consequently, $T_{\Delta E}(^3\text{Be})$ is not likewise suppressed by excluded volume effects, making it difficult to
simultaneously account for the similarity of $T_{\Delta E}(^4\text{He})$, $T_{\Delta E}(^3\text{Li})$, and $T_{\Delta E}(^3\text{Be})$ and the reduction of all three relative to $T_{\Delta E}(\text{He-Li})$. This suggests that the method described in Ref. [14] to reconcile excited state and isotope

temperatures may not be supported by the present data.

Alternatively, the much larger values for $T_{\Delta E}(\text{He-Li})$ may reflect differences in the emission environments of $^3\text{He}$ as compared to the emission environments for fragments and alpha particles. Investigations of fragment-fragment correlations [33] and fragment charge distributions [33,34] have reported evidence for a hierarchy of timescales whereby light particle emission precedes fragment emission rendering the two processes out of equilibrium. Predictions of dynamic models for light particle emission and statistical emission rate approaches [27,29] also support this picture. Determination of the precise degree to which light particle emission during the early stages of the collision is further enhanced by statistical emission of predominantly light particles at very

high initial temperature depends on the time scale for thermalization and requires further experimental and theoretical

investigations. Qualitatively, however, both effects will cause a divergence of temperatures derived from poorly bound light particles such as $d$, $t$, $^3\text{He}$ from those derived from strongly bound fragments observed in the present work.

In summary, populations of the states $^4\text{He}$, $^5\text{Li}$, and $^8\text{Be}$ and double ratios constructed from the yields $^3\text{He}$, $^6,^7\text{Li}$, $^{11,12,13}\text{C}$ isotopes were measured for central

Kr+Nb collisions at $E/A = 35-120 \text{ MeV}$. These ratios were used to extract apparent temperatures for emission using Eqs.

(1) and (2). Consistent and approximately constant apparent
temperatures were obtained from the excited states of $^4\text{He}$, $^5\text{Li}$, and $^8\text{Be}$ nuclei and from the yields of carbon isotopes. In contrast, apparent temperatures obtained from ratios of helium isotopes increase monotonically with incident energy. This discrepancy may be consistent with a preference for $^4\text{He}$ emission during the early stages of the collision and enhanced fragment emission at a lower temperature during a later stage.

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