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Decay of instable Li, Be, and B fragments and the distortion of temperature measurements in heavy ion collisions

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The recent attempts to extract the temperature in the late stage of medium energy (20—60 MeV/nucleon) heavy ion collisions from the yields of γ- and particle-instable fragments are discussed. The quantum statistical model is employed to demonstrate that feeding from instable states distorts the yields used for the temperature determination severely. Some particle instable fragments are only moderately affected by feeding. These selected species can still be useful for determining the temperature. The breakup temperatures of the fragment conglomerate extracted with this method are $T \simeq 4$—8 MeV, much smaller than the corresponding slope factors, which indicate $T \sim 15$ MeV.

Morrissey *et al.* recently suggested that the temperatures achieved in heavy ion collisions can be determined from the ratio R of the yield of γ-instable Li, Be, and B fragments to the corresponding ground state yield.[1] In thermodynamic terms $R \sim \exp(-\Delta E_i/T)$, where ΔE_i is the energy gap between the excited state and the ground state, and hence the knowledge of R should be sufficient to know the temperature in the system.

The surprising result of the measurement was that the ratios of the yield of γ-*instable* to ground state fragment yields, e.g., ^{7}Be* (478 keV)/^{7}Be(g.s.) give $T \approx 0.5$ MeV, if the simple Boltzmann ansatz proportional to $\exp(-\Delta E/T)$ is used for the yield ratio. Also for several other ratios the experimentalists observed very small R values, consistently indicating temperatures $T < 1$ MeV (Refs. 1—3) at MSU/GANIL bombarding energies, $E_{\rm lab} \simeq 20$—60 MeV/nucleon. These temperature values are in striking contrast to the temperatures $T \simeq 15$ MeV extracted previously from the slopes of the single particle inclusive spectra of Li, Be, and B fragments[4] and light particle spectra[5] at these bombarding energies. The T values of Refs. 1—3 seem to be unreasonably low at c.m. energies of $\simeq 10$ MeV/nucleon.

Another group at Michigan State University (MSU) has complemented the previous measurements with data on the yield ratios of *particle instable states*.[6—8] Here the same ansatz as in Refs. 1—3 was used, but much larger temperature values, $T \simeq 5$ MeV, were obtained for similar reactions using ratios like ^{5}Li*(16.66 MeV)/^{5}Li(g.s.).

In the present paper we try to analyze the origin of these confusing results. As the theoretical framework we employ the quantum statistical model (QSM) of Ref. 9. It is shown that sequential feeding, i.e., decay of particle instable nuclei after the disassembly of the system, affects the yield ratios dramatically. The original idea[1] that the ratios of γ-instable to ground state yields can be useful for a temperature determination turns out to be impracticable for temperatures $T > 2$ MeV. At higher temperatures the feeding is so strong that the yield ratios can actually decrease slightly with increasing temperature. In fact, recent experiments[3] on the excitation function of the temperature using compound nucleus formation exhibit exactly this behavior, and also show a maximum in the apparent temperature $\tilde{T}$ which agrees with our calculated value, $\tilde{T}^{\rm max} \simeq 2$ MeV.

Some relative populations of selected particle instable states appear to be affected only moderately for temperatures $T < 10$ MeV,[6—9] and can still be useful for measuring the temperature. At higher temperatures, $T \gg \Delta E$, this method is inapplicable, since the relative populations reach the asymptotic ratio given by the statistical weights. In a recent publication[10] we showed that higher temperatures, $T > 10$ MeV, can be determined from the observed pion to proton ratios.

The present paper employs the quantum statistical

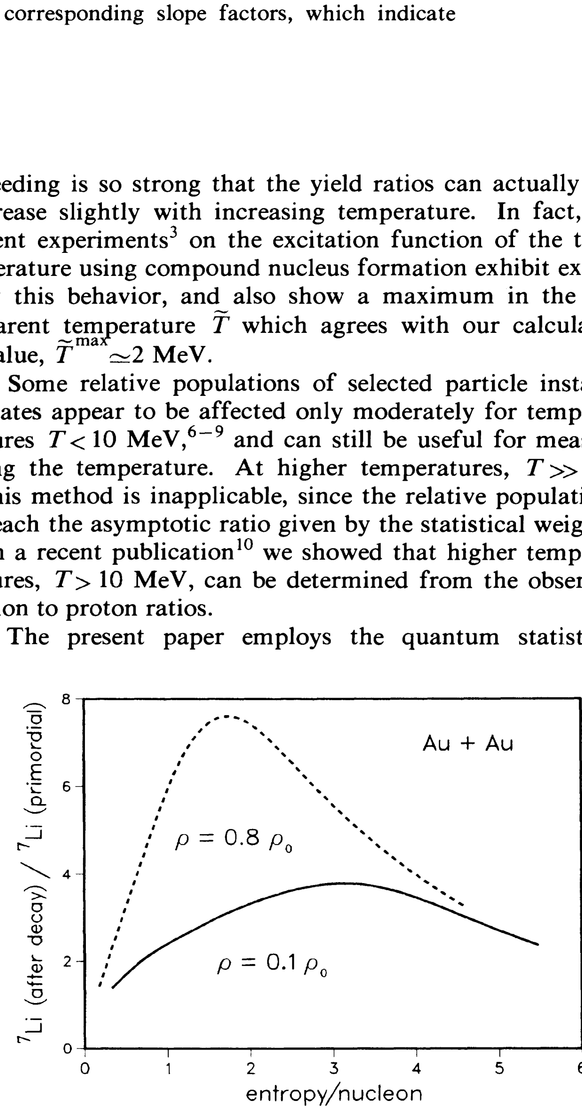

FIG. 1. Ratio of ^{7}Li in the ground state after the decay of instable fragments versus primordial ^{7}Li for the Au + Au system. Two breakup densities have been used, $\rho = 0.1\rho_0$ (solid line) and $\rho = 0.8\rho_0$ (dashed line).

model of Ref. 9. The system of A nucleons is considered in the grand canonical ensemble. A large variety (≈ 600) of stable and instable fragment species with the appropriate degeneracy, binding energy, and quantum statistical distribution function is considered, and the thermodynamic properties of the resulting mixture of fragments are computed. The decay of the particle- and γ-instable states is taken into account in the second stage of the calculation which then yields the final distributions of the ≈ 100 stable fragment species. A similar, but *classical* model has been developed independently by Randrup, Koonin, and Fai.[11] In these statistical models it is assumed that thermal and chemical equilibrium are established during the expansion of the system. If the expansion is isentropic, then the temperature and density drop drastically from the high initial values.[9] Therefore, the high temperatures which reflect in the slopes of the spectra should be accompanied by much smaller temperatures which characterize the fragment yields. At the later disassembly time also the chemical abundance and the momentum distribution of each species of fragment freeze out.[9,11–13] After this freezeout the fragment yields change again due to the subsequent decay of instable states. We include ≈ 100 stable and β-active nuclei up to mass number 130 and ≈ 500 instable light nuclei with $A < 20$. The yield of each species is determined from its chemical potential μ_i, its statistical weight g_i, and the temperature via nonrelativistic Bose and Fermi distributions for i species. The chemical potential of a cluster in equilibrium is given by the chemical potentials of its constituents and its binding energy E_i (Refs. 9 and 14)

$$\mu_i = Z_i \mu_P + N_i \mu_N + E_i \ ,$$

with

$$E_i = Z_i m_P c^2 + N_i m_N c^2 - m_i c^2 \ ,$$

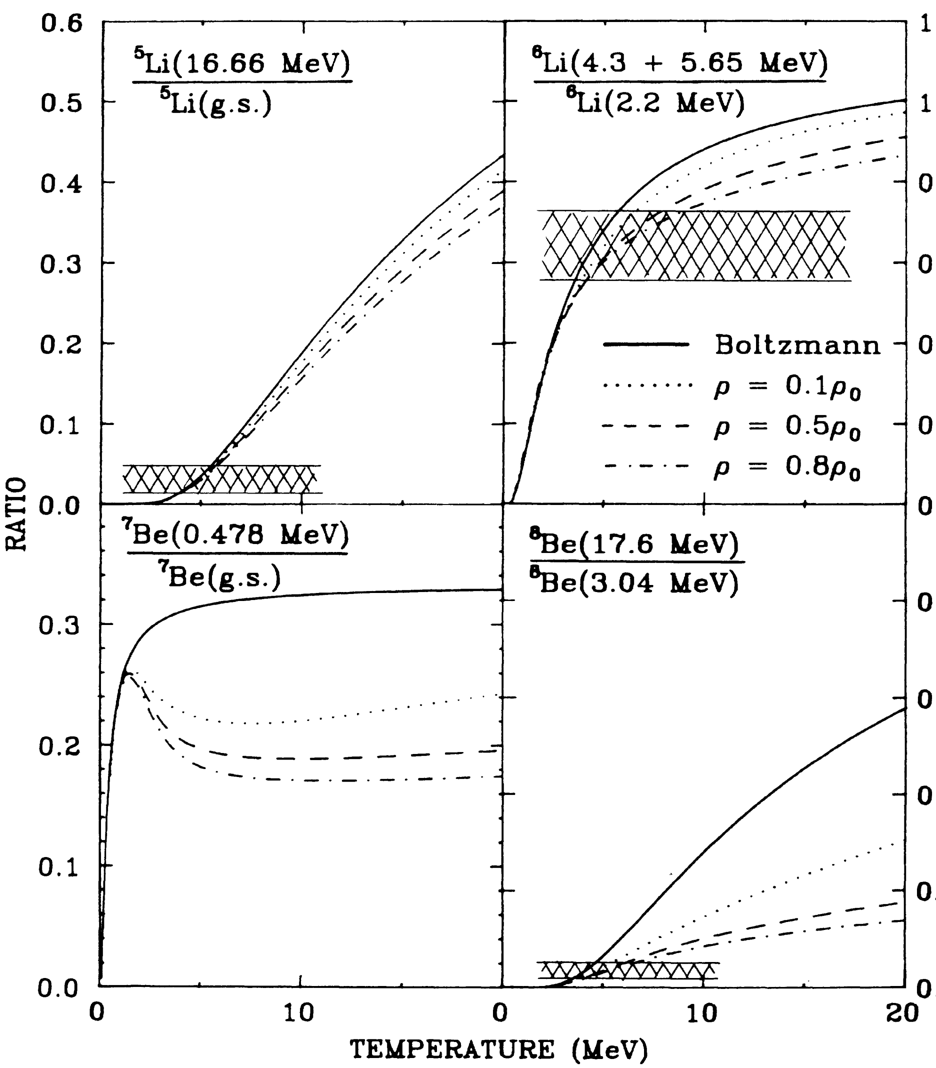

FIG. 2. Ratios of excited states to ground states (or other excited states in the upper right) for Ar + Au versus the temperature for three breakup densities. Solid lines show the ratio in the case of a pure Boltzmann distribution, shaded areas show the experimental ratios (Refs. 6–8).

where Z_i is the proton number of species i and N_i is the neutron number of species i. The fragments are treated as hard spheres of fixed volume in the present context. Then the total volume V_T can be calculated as the sum of the available and the excluded volume

$$V_T = V + V_{\rm excl} = V + A/\rho_0 ,$$

where A is the total number of nucleons. This leads to the expression

$$\rho = \frac{A}{V_T} = \frac{\rho_{\rm pp}}{1+\rho_{\rm pp}/\rho_0} .$$

Here $\rho_{\rm pp} = \rho_{\rm pointparticle}$.

The actual calculation consists—at a given temperature—of a search for the chemical potentials of protons and neutrons, which yield the desired N/Z ratio and density.

The experimental information needed for this calculation was extracted from the tables of Ajzenberg-Selove.[15] Here we find the statistical weights, the binding and excitation energy of each fragment, as well as the various sequential decay channels used after breakup in the evaporation calculation.

To determine which specific level of a daughter nucleus is populated by a decay process, we derive the transition probability to this level for each orbital angular momentum of the emitted particle. The barrier penetrability factor is calculated using the Wentzel-Kramers-Brillouin (WKB) approximation.

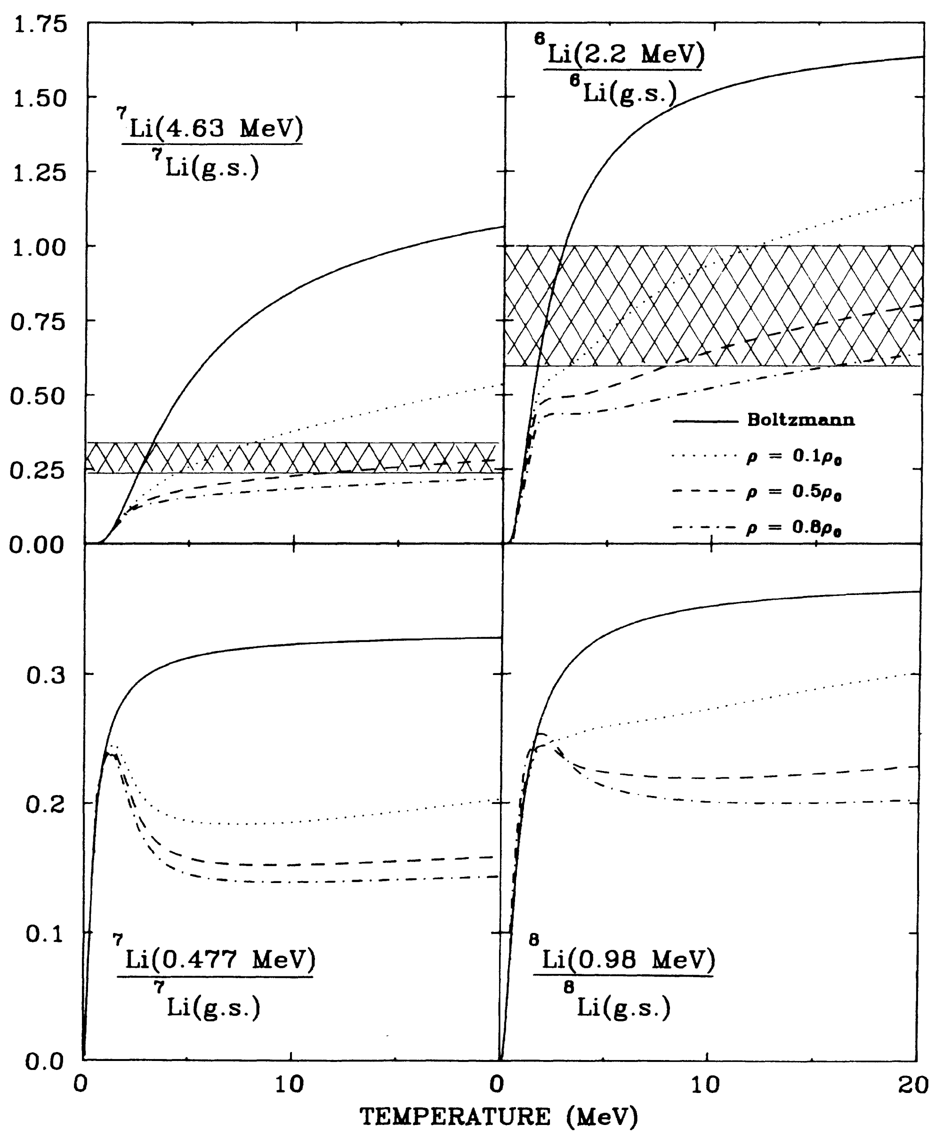

FIG. 3. Same as Fig. 3, but for Li states only.

$$P_{l,E}=\sqrt{E} \text{ no barrier}$$

$$=\sqrt{E}\exp\left[2\left\{kRx-\eta\left[\frac{\pi}{2}+\arcsin\left[\frac{\eta-kR}{\eta^2+(l+\frac{1}{2})^2}\right]\right]-(l+\tfrac{1}{2})\log\frac{x(l+\frac{1}{2})+\eta+(l+\frac{1}{2})^2/k^2R^2}{[\eta^2+(l+\frac{1}{2})^2]^{1/2}}\right\}\right],$$

where $R=(1.25A^{1/3}+1.3)$ fm is the potential radius, E is the transition energy, and

$$\eta=Z_1Z_2\frac{e^2}{\hbar c}\left[\frac{mc^2}{2E}\right]^{1/2},$$

$$k=(2\mu c^2E/\hbar^2c^2)^{1/2},$$

$$x=\left[\frac{2\eta}{kR}+\frac{(l+\frac{1}{2})^2}{(kR)^2}-1\right]^{1/2}.$$

The phase space factor for a transition with a fixed l value is given by a sum over all possibilities to couple l and the spin of the emitted particle to a total spin j, which is compatible with the spins of parent and daughter nucleus.[16]

Possible l values are given by triangle rules involving the spins of parent, daughter, and emitted particle. Summation over all l values then yields the relative probability of this particular level, compared to other possible levels in the daughter nucleus. γ-instable states always decay into the ground state.

Let us now discuss the predictions of the QSM for the population of γ- and particle-instable nuclei. The main reason for the failure of the simple temperature formula[1–3] is the distortion of the yields of the ground state population of the complex fragments due to the feeding from the subsequent decay of more massive particle-instable complex fragments: Figure 1 shows the ratio of the ^{7}Li yields before and after the decay of the instable states has taken place. Observe that distortions of factors $\simeq 8$ are reached at entropies $S/A \simeq 1.5$–2. Note that the distortions are less pronounced for smaller breakup densities.

Figure 2 shows that the amount of feeding from sequential decay is different for different species: In the case of ^{7}Be (lower left-hand side), drastic feeding (mainly to the ground state) from heavier particle-instable fragments sets in as early as at $T \approx 2$ MeV. For $T > 3$ MeV, a ratio of ≈ 0.2 is obtained, independent of the actual temperature. Hence this ratio turns out to be impracticable for temperature measurements at $T > 2$ MeV. At these higher temperatures the feeding is actually so strong that the yield ratios can literally decrease somewhat with increasing temperature. In fact, recent experiments[3] on the excitation function of the temperature using compound nucleus formation exhibit exactly this behavior, and also show a maximum in the apparent temperature $\widetilde{T}$ which

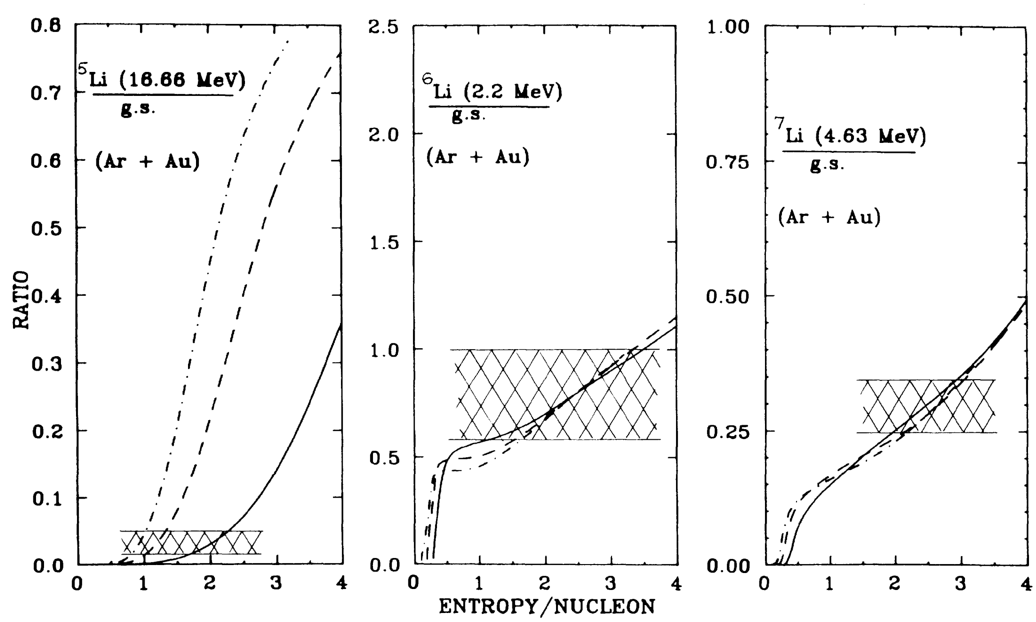

FIG. 4. Three ratios of particle instable states to ground states versus the entropy/nucleon in the Ar + Au system. Three different breakup densities are used, $0.1\rho_0$ (solid line), $0.5\rho_0$ (dashed line), and $0.8\rho_0$ (dotted-dashed line). Shaded areas show the experimental ratios (Refs. 1–3, and 6–8.)

agrees with our calculated value, $\tilde{T}^{max} \simeq 2$ MeV.

However, note also that some ratios of particle-instable states in the weakly bound ^{5}Li and ^{6}Li nuclei (upper part of figure) show only a moderate distortion induced by the sequential decay as long as $T < 10$ MeV. Therefore the Boltzmann ansatz might be a useful approximation in these cases. Temperatures of $T \approx 5$ MeV can be estimated from some of the measured ratios in Ar + Au collisions at 60 MeV/nucleon.[6–8]

These values are much lower than the corresponding slopes of the energy spectra of the particles, which yield $T = 10$–20 MeV.[4,5] These low values fit, however, in the systematics of the "too small" temperatures, $T = 12$–20 MeV, obtained from 4π data on light fragment emission at much higher energies, $E_{lab} \simeq 0.4$–1 GeV/nucleon.[9]

A note of caution: Observe the lower right-hand side of Fig. 2: Even though the ratio of two high-lying states—*both* particle instable—of ^{8}Be is considered, we do observe a strong distortion due to feeding from other states which had been overlooked before.[6] Therefore, care must be taken in using these ideas to measure the temperature.

Figure 3 shows the tremendous distortions to be expected in ratios of γ-instable—to ground state yields of ^{6}Li, ^{7}Li, and ^{8}Li—fragments. Here it is predominantly the feeding to the ground state which limits the possibility of measuring the temperature. Some of these states seem to be, however, interesting candidates for possible future entropy measurements: the feeding has the effect of resulting in a rather nice one-to-one relation between ratios of ^{6}Li and ^{7}Li low lying states to ground states and the entropy; see Fig. 4. These states can be useful for entropy determination: The data[1–3,6–8] are compatible with $S/A \simeq 1.5$–3, which is in accord with the entropy values determined at the same energies from the mass yield distributions.[4,9]

It should be noted that stable and instable medium mass fragments also play an important role in determining the entropy from deuteron to proton ratios: They also alter the relation $S/A\,(R_{dp})$ dramatically.[9]

We have presented QSM calculations for the feeding of complex fragment yields due to decay of instable fragments. We have shown that the feeding distorts simple methods to extract the temperatures; in particular it renders the γ-instable states practically useless for determining the temperature. These states are, however, interesting candidates for determining the entropy.

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