INFLUENCE OF SECONDARY DECAY ON ISOTOPE-RATIO TEMPERATURE MEASUREMENT

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In intermediate energy heavy ion collisions, nuclear fragments are emitted from highly excited systems. Production of these particles appears to be dominated by their phase space, and can be described by statistical physics. Thus, temperature, a basic quantity in statistical physics, can be addressed experimentally. Two methods have been most commonly used to measure nuclear temperatures, both of which assume thermal and chemical equilibrium at a single freeze-out condition. One method is to measure the yields of particle unstable states [1]. Another method is based on the double ratio of two isotope pairs [2].

Most work on temperature has focused on the measurement of excited states yields [1], where temperature is deduced from the yields of two states in one isotope

$$T = \frac{E_1 - E_2}{\ln(a' Y_1 / Y_2)}. \qquad (1)$$

Here a' = $(2J_2 + 1)/(2J_1 + 1)$, E_i is the excitation energy, Y_i is the measured yield and J_i is the spin factor of the state i. Experimental results show that temperature extracted from Eq. (1) increases slowly from 3 MeV to 6 MeV over a large range of incident energy [3].

Recently, nuclear temperatures also have been studied using double isotope yield-ratios [2,3]. Yields of two pairs of isotopes, each with one neutron difference, are measured and temperature is defined as

$$\mathrm{T} = \frac{B}{\ln(a(Y_1 / Y_2) / (Y_3 / Y_4))} \qquad (2)$$

where Y_1, Y_2 are the yields of one isotope pair and Y_3, Y_4 is another isotope pair; B is the binding energy difference, $B=BE_1-BE_2-(BE_3-BE_4)$. Here, the statistical weighting factor a is defined as

$$a = \frac{(2S_3 + 1) / (2S_4 + 1)}{(2S_1 + 1) / (2S_2 + 1)} \bullet \left[\frac{A_3 / A_4}{A_1 / A_2} \right]^{1.5} \qquad (3)$$

where S_i is the ground state spin factor and A_i is the mass number of the isotope i. The mass factors arise from the integration over phase space volume.

Sequential feeding often lowers the apparent temperature. Inclusion of continuum states amplifies this effect. For illustration, we perform sequential calculations for the system Au+Au. The experimental charge distribution of $Z^{-2.5}$ at excitation energy of 13.2 A.MeV [4] was used to constraint the calculation. Figure 1 shows the apparent isotope temperature T_{HeLi} as a function of the input (emission) temperature. Sequential decay calculations including only known bound states and resonances are shown by the dotdashed line. There is a monotonic dependence between T_{HeLi} and T_{em} even though the sensitivity to T_{HeLi} decreases with increasing temperature. For reference, the dotted line represents calculations with no secondary decay. Without the influence of secondary decay, the calculated isotope temperature is nearly the same as the input temperature. However, when continuum states are included, the calculation flattens out at T_{em} >7 MeV as shown by the solid line. Inclusion of sequential decay contributions from the continuum enhances decays to low-lying states and renders T_{HeLi} insensitive to the emission temperature at high excitation energy [4].

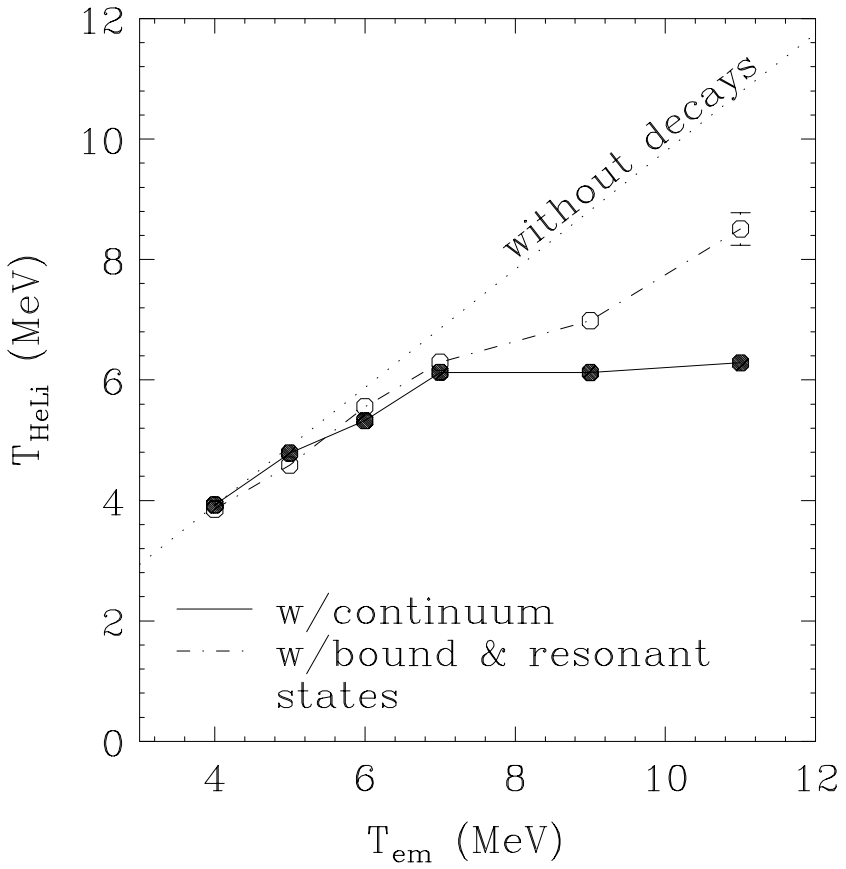

Fig. 1 : Calculated T_{HeLi} as a function of input temperatures T_{em} by including different excited states.

Following Equation (2), the isotope temperature can be determined from the yield of ratios of two pairs of isotopes. Within each pair, the two isotopes differ from each other by one neutron number. If there were no influence from the secondary decay, any combination of isotope pairs, i.e. thermometers, fulfilling this condition should yield the same temperature. However, recent studies of more than 1300 thermometers reveal that the apparent temperatures are highly dependent on the particular isotopes used [5]. In general, fluctuations arising from different thermometers are largest for those with small values of binding-energy parameter, B in Eq. (2).

Thermometers with large B fluctuate less but require one pair of the isotopes used in Eq. (2) to include one strongly bound stable nucleus and one neutron deficient nucleus, so the pair has a large binding energy difference. Since alpha particles are strongly bound, the isotope pair, (^{3}He, ^{4}He), provides many isotope thermometers with B>10 MeV which have been studied extensively (for example, see ref. [6]). The (^{11}C,^{12}C) isotope pair also has a large binding energy difference arising from the strongly bound ^{12}C and the neutron deficient ^{11}C nuclei. Thus, one can form many double isotope yield-ratios using (^{11}C,^{12}C) isotopes. Due to low cross-section and the difficulty in isotope separation, the thermometers involving heavier isotope ratios such as (^{11}C,^{12}C) have been less studied experimentally [5].

The bottom panel of Figure 2 shows the calculated isotope temperatures of Eq. (2) according to increasing B for T_{em}=4.4 MeV. Before sequential decays, the calculated temperatures from primary ground state yields (Eq. 2) are independent of specific isotope ratios used, at T_{em} as shown by the dotted line. After sequential feedings, the calculated apparent temperatures fluctuate (open points).

The calculated values in Fig. 2 are mostly below 4.4 MeV. The exception is the one involving (^{9}Be, ^{10}Be) ratio whose apparent temperature is above 7 MeV. To show the fluctuations more clearly, dashed

lines are drawn to guide the eye. The trends of the fluctuations (high and low values) are similar to those observed experimentally in the central Au + Au collisions at E/A=35 MeV.

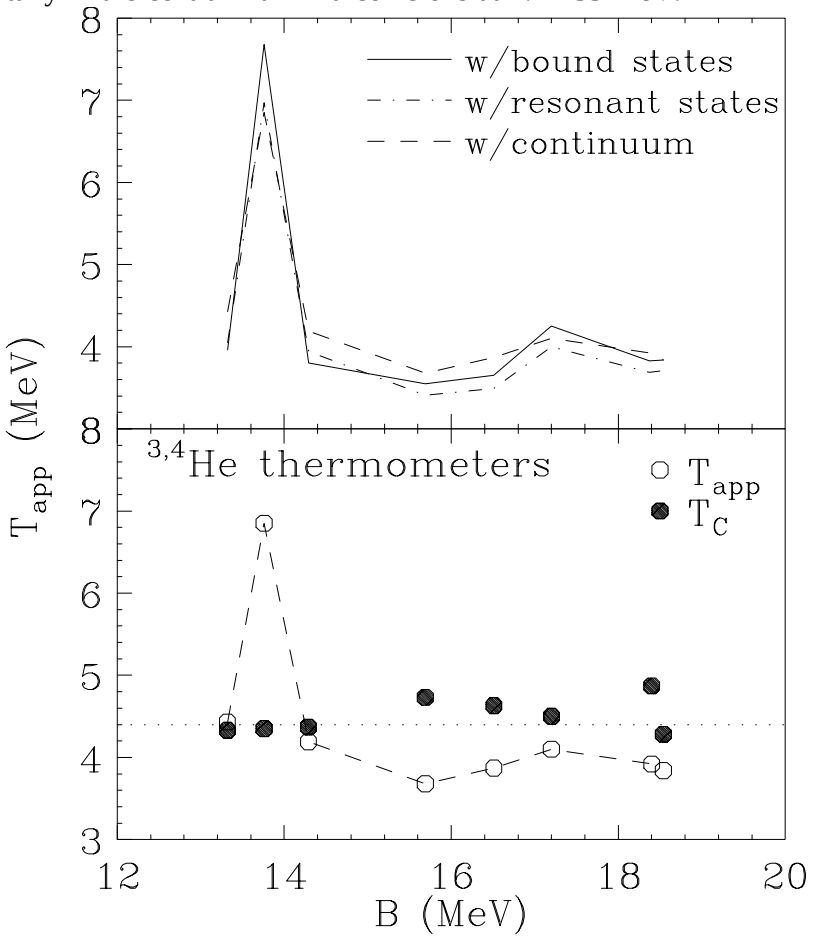

Fig. 2 : Calculated T_{app} as a function of binding energy difference, B (bottom panel) for isotope ratios involving ^{3}He, ^{4}He.

To study the effects of different contributions from sequential decays to the fluctuations, calculations were performed by including different classes of excited states. The solid lines in the top panels of Fig. 2 represent apparent temperatures predicted by calculations where only observed discrete bound states are included in the sequential decay calculations. For the He thermometers, when known particle unbound resonances, are included, the fluctuations change slightly (dotdashed lines). Finally, when contributions from the higher states in the continuum are included, there are slightly more changes (dashed lines).

Similar studies have been performed for the thermometers involving (^{11}C, ^{12}C) as shown in Fig. 3. Compared to He thermometers, the effects of including more states are much larger. For example, most of the (^{11}C, ^{12}C) thermometers calculated from sequential decays including bound states only (solid line, upper panel) are a few MeV's higher than the temperatures including more states. The effect of inclusion of known particle unbound resonances (dotdashed lines) and states in the continuum (dashed lines) lower the temperature to around 3 MeV, much below the input temperature of 4.4 MeV. In many experimental measurements, the (^{11}C, ^{12}C) thermometers provide apparent temperatures around 4 MeV, somewhat higher than these illustrative results.

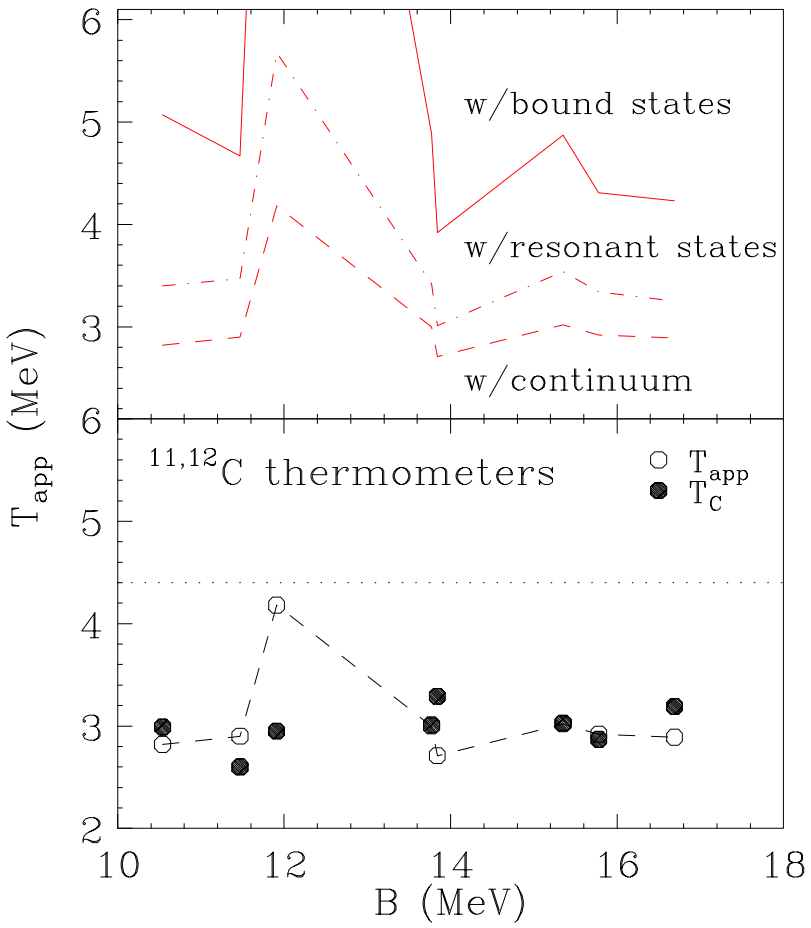

Fig. 3 : Calculated T_{app} as a function of binding energy difference, B (bottom panel) for isotope ratios involving (^{11}C, ^{12}C). Top panels shows three calculations with different types of excited states included.

It is not clear why the current model fails to predict the carbon temperatures. One problem is the inability of the current calculations to predict the carbon isotope distributions [1]. The calculated distributions are much narrower than the experimental ones. In addition, the model tends to over-predict the number of particles decaying to the ground state of the stable and neutron rich nuclei such as ^{12}C, ^{13}C and severely under-predicts the yield of neutron deficient nuclei such as ^{11}C. More work is clearly needed to understand the effect of sequential decays on the temperatures extracted from these heavy isotopes.

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