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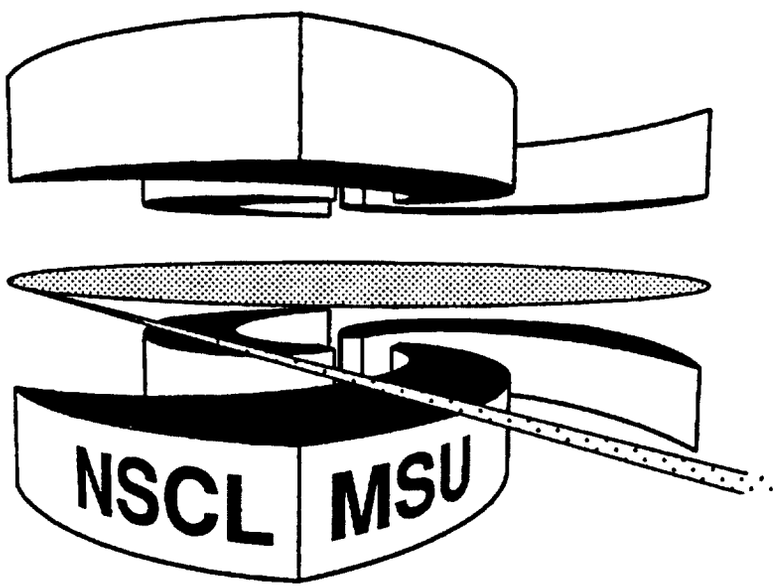

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Nuclear Temperature Measurements with Helium isotopes

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Abstract

Ten isotope double ratios, all involving yield ratios of ^3He and ^4He are studied in the central and peripheral $Au + Au$ collisions at 35A MeV. Correction factors which remove the fluctuations in the measured isotope temperatures have been extracted. These factors provide baseline corrections for sequential decay effects for temperatures less than 4.5 MeV. Sequential decay calculations reproduce these correction factors and predict an identical saturation in the apparent isotope temperatures based on ratios of $^{3,4}He$ isotopes and the temperatures constructed from excited and ground state populations of ^4He. The comparison of these quantities provides an important test for non-equilibrium effects.

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When experimental observables are dominated by the available phase space, the concept of temperature can play an important role in simplifying the theoretical description of the decaying nuclear system [1-15]. Temperatures achieved in nuclear collisions have been deduced by comparing the slopes of energy spectra[2-3], relative populations of excited states[4,5] and the isotope yields[6-15] to statistical model calculations. Kinetic energy spectra are easily influenced by undamped collective motion [16] and may not be suitable for tests of chemical equilibrium in systems where such collective motion is present. Temperatures derived from the relative populations of states widely separated in excitation energy [4,5] or from the relative yields of isotopes with very different binding energies [6-15] test chemical equilibrium directly and are insensitive to collective motion.

Consistency between suitable thermometers provides an important test of the degree of thermalization achieved in a reaction. Temperatures extracted from measurements of excited state populations or isotope yields, however, often differ from one set of isotopes or pair of excited states to another [9-14]. While these variations may sometimes reflect nonequilibrium processes [3,17], calculations have shown that significant differences arise from the feeding from the secondary decay of heavier particle unbound nuclei [8-13]. In this paper, we show that secondary decay effects are responsible for some of the discrepancies reported for isotope ratio thermometers involving He isotopes, and propose definitive tests to distinguish between the various explanations for the discrepancies that remain.

To investigate these issues, a 5 mg/cm^2 Au target was bombarded by a 35A MeV Au beam from the K1200 cyclotron of the National Superconducting Cyclotron Laboratory at Michigan State University. Measurements were performed with the Miniball 4π array[18] which provided impact parameter selection via the charge particle multiplicity N_C at $23° \leq \theta_{lab} \leq 160°$ and the Multics[19] high resolution hodoscope which measured isotope yields at $3° \leq \theta_{lab} \leq 23°$. Within this latter angular domain, isotopic yields were determined for: 1) fragments emitted from the central source at $v_{lab} \geq 0.14c$ in central collisions ($N_C \geq 22$: innermost 20% of the reaction cross section) and 2) fragments emitted at $v_{lab} \geq 0.27c$ from the projectile-like residue in peripheral collisions ($4 \leq N_C \leq 9$).

Temperatures can be obtained, in the limit of local thermal equilibrium, from the ground state yields of two pairs of isotopes according to the expression [6]

$$T_{iso} = \frac{B}{\ln(a \cdot R_{iso})}; \tag{1}$$

where $R_{iso} = \frac{Y(A_i,Z_i)/Y(A_i+1,Z_i)}{Y(A_j,Z_j)/Y(A_j+1,Z_j)}$ is the double yield ratio of the specific pairs of isotopes, $B = B(A_i, Z_i) - B(A_j,\ Z_j) + B(A_j + 1,\ Z_j) - B(A_i + 1,\ Z_i)$ is the difference between corresponding ground state binding energies, and **a** is a statistical factor involving the ground state spins[6-9]. Similarly for equilibrated systems, temperatures can be obtained from the yields of two states in the same isotope according to the expression

$$T_{ex} = \frac{E_2^* - E_1^*}{\ln(a_{ex} \cdot R_{ex})}; \tag{2}$$

where $R_{ex} = Y_1/Y_2$ is the ratio of the yield of the upper state divided by the yield of the lower state and $a_{ex} = (2J_2 + 1)/(2J_1 + 1)$ is a statistical factor involving the spins J_1 and J_2 of the two states with excitation energies E_1^* and E_2^*.

Temperatures extracted via Eqs. (1) and (2) are often termed "apparent temperatures" reflecting the fact that the ratios R_{iso} and R_{ex} can be strongly modified by secondary decay contributions to the measured yields. For simplicity, one can group these yield corrections to the ground state double ratio R_o for an equilibrated system via

$$R_{app} = \kappa R_o \tag{3}$$

where κ takes into account sequential decays from higher lying excited states and depends strongly on the particular double ratio chosen. From Eq. 1 and 3, T_{app} can be written as [9]

$$\frac{1}{T_{app}} = \frac{1}{T_o} + \frac{\ln \kappa}{B} \tag{4}$$

where T_o is the breakup or emission temperature and the factors $ln\kappa/B$ account for fluctuations seen in the measured temperatures[9].

Closed cirlces in Figure 1 show the apparent temperatures extracted via Eq. 1 as a function of B for fragments emitted from the central source in central collisions (upper panel)

and from the projectile-like residue in peripheral collisions (lower panel). The corresponding isotope ratios and the values for a and B values are listed in Table I. To show that the observed fluctuations in the apparent isotope temperature arise mainly from secondary decays, sequential decay calculations that take into account of all tabulated discrete states as well as unbound states in the continuum have been performed. In the present calculations [8,10] particles are assumed to be emitted at freeze-out by a thermalized source of temperature T_{em}. The population of an excited level of a nucleus at excitation energy E_i^*, spin J_i, neutron number N_i, charge number Z_i and lifetime t_i, was assumed to be of the form [8]

$P_i(N_i\ ,\ Z_i\ ,\ E_i^*,\ J_i, \mu_p,\ \mu_n,\ T_{em})_\propto$

$(2J_i+1)\cdot(N_i+Z_i)^{1.5}\exp(-\frac{V_i}{T_{em}}+\frac{Q_i}{T_{em}})\exp(-\frac{E_i^*}{T_{em}})\exp(-\frac{Z_i\mu_p+N_i\mu_n}{T_{em}})\cdot\exp(-t_b/t_i)$, (5)

where V_i is the Coulomb barrier, $-Q_i$ is the separation energy for emission of this nucleus from a residue of mass number A_o and charge number Z_o. T_{em} is the emission temperature and $\exp(-t_b/t_i)$ is a factor which suppresses the emission of very short-lived nuclei[8]. The breakup time-scale t_b is assumed to be 100 fm/c. At each T_{em} the "chemical potentials", μ_p and μ_n, were treated as free parameters to reproduce the experimental charge distributions[8,10] which are parametrized by a power law, $Y(Z) \propto Z^{-\tau}$[20], and to constraint the charge to mass ratio of the emitted particles to be consistent with that of the total system. Typical uncertainties in the calculations are less than 5% due to unknown spins and parities of tabulated discrete states. Further computational details can be found in ref. [8].

The emission temperatures of the break up system were obtained by comparing the measured double ratios R_{app} of Eqs. 1 and 2 to sequential decay calculations. The deduced emission temperatures of the system are obtained by evaluating the χ^2 for the calculated and experimental ratios:

$$\chi^2_\nu(T_{em}) = \frac{1}{\nu}\sum_{i=1}^{\nu}\frac{[R_{expt,i}-R_{calc,i}(T_{em})]^2}{\sigma^2_{expt,i}+\sigma^2_{calc,i}} \qquad (5)$$

Here the summation is over the ten isotope thermometers. $R_{expt,i}$ are experimental double yield ratios and $R_{calc,i}(T_{em})$ are theoretical ratios calculated in analogy to the experimental $R_{expt,i}$ using the results from the sequential decay calculations. Minimum $\chi^2(T_{em})$ values,

$T_{em} = 4.4 \pm 0.2$ MeV and 3.5 ± 0.3 MeV are thereby obtained for central and peripheral $Au + Au$ reactions, respectively. The calculated apparent temperatures corresponding to these emission temperatures (open squares, Fig. 1), well reproduce the experimental data. The breakup temperatures for central Au+Au collisions in the same experiment determined from the relative populations of excited states of ^{5}Li, ^{4}He and ^{10}B fragments is 4.2 ± 0.6 MeV [10,22], consistent with the isotope temperature within the experimental uncertainties.

If one compares the upper and lower panels of Fig. 1, it is clear that high (low) temperature values in the upper panel correlate with high (low) temperature values in the lower panel and that this correlation is relatively well reproduced by the secondary decay calculations. For isotope ratios derived from yields of fragments with $Z \geq 3$, it was demonstrated in ref. [9] that these secondary decay correlations are not particularly system dependent and for temperatures of the order 4 MeV, can be characterized by the factor $ln\kappa/B$ in Eq. 4 and utilized as a first order correction to secondary decay in other reactions. The values of $(ln\kappa/B)_{expt}$ and $(ln\kappa/B)_{calc}$ obtained from Eq. 4 assuming $T_o = T_{em} = 4.4$ MeV are listed in Table I.

These values for $(ln\kappa/B)_{expt}$ allow a straightforward first order correction to the apparent temperature that may be useful at low to moderate temperature. The mean "corrected" temperatures for peripheral Au+Au collisions (lower panel of Fig. 1) obtained according to Eq. 4 using the measured apparent temperatures and the $(ln\kappa/B)_{expt}$ values is 3.5 MeV, identical to the emission temperature obtained from sequential decay calculations. The left panel in Figure 2 shows three different isotope ratio temperatures as a function of excitation energy obtained by Ma et al [12,21] using isotope ratios of ($^{6,7}Li$, $^{3,4}He$), ($^{2,3}H$, $^{3,4}He$) and ($^{1,2}H$, $^{3,4}He$). The right panel shows that these isotope ratio temperatures display a common dependence after "corrections" for $(ln\kappa/B)_{expt}$ values via Eq. 4. Similar discrepancies between isotope temperatures have been removed for the following systems: 1.) $Ca + Ni$, $Ar + Ni$, $Ca + Fe$, $Ar + Fe$ collisions at 33A MeV[13]; 2.) $Xe + Cu$ collisions at 30A MeV [22]; 3.) Central $Au + Au$ collisions at 50-200A MeV[14,15]; 4.) peripheral $Au + Au$ collisions at 1000A MeV[14,15]; 5.) $N + Ag$ and $N + Au$ collisions from 30-100A

MeV [23]; 6.) $Ar + Sc$ at 50-150 MeV[24] and 7.) $Kr + Nb$ at 35-120 MeV[24]. For all these systems, the major source of discrepancies between isotope temperatures is the lack of adequate corrections for secondary decay.

The correction factors κ in Eq. 3, however, are predicted to be temperature dependent [8]. An examination of the temperature dependence of the individual yields that comprise these ratios may suggest experimental tests whereby the predicted temperature dependence may be confirmed or rejected. To illustrate the various factors that govern this temperature dependence, we have calculated the secondary decay corrections to the yield ratios for the isotope pairs: $Y(d)/Y(t)$, $Y(^6Li)/Y(^7Li)$, $Y(^7Li)/Y(^8Li)$, $Y(^8Li)/Y(^9Li)$, $Y(^9Be)/Y(^{10}Be)$, $Y(^{11}B)/Y(^{12}B)$, $Y(^{12}B)/Y(^{13}B)$, and $Y(^3He)/Y(^4He)$ as a function of temperature under the constraint that the final calculated charge distributions satisfy a power law distributions $Z^{-2.5}$[25]. Except for $Y(^3He)/Y(^4He)$, the single ratios shown in the left panel of Fig. 3 remain approximately constant at $T_{em} > 5$ MeV. All the information in the left panel can be condensed to a single temperature dependent number T_o obtained by using Eq. 4 and values of $(ln\kappa/B)_{calc}$ for the various double ratios from Table I. The resulting values for T_o, given by the solid line in the right panel, increase with T_{em} until $T_{em} \approx 6$ MeV where they attain asymptotic values of about $T_o \approx 6$ MeV[25]. Both the ratio $Y(^3He)/Y(^4He)$ and therefore T_o remain roughly constant at $T_{em} > 6$ MeV because the increased primary emission of ^3He relative to ^4He is canceled out by the increased secondary yields of ^4He from the α decay of heavier fragments. The difference between T_{em} and T_o can be viewed as an indication that the secondary decay correction factor κ should actually be temperature dependent.

Recent experimental determinations of T_{iso} from the ($^{6,7}Li$, $^{3,4}He$) double ratio for $Au + Au$ collisions at significantly higher incident energies have yielded higher apparent temperatures [14] up to 8 MeV that cannot be reproduced via calculations like these, which include the secondary decay of the particle unbound continuum [8]. Furthermore, the experimental isotope temperatures differ from the temperatures extracted from the excited states of ^5Li, ^4He and $^8Be(T_{ex} \cong 4$ MeV) [14]. Our calculations predict that apparent temperatures extracted from the ratio of the yield of the ^4He ground state to the yield of its

0^+ excited state at 20.1 MeV ($T(^4He^*)$, dashed lines in Fig. 3) should be nearly identical to the values for T_o extracted from the ($^{6,7}Li$, $^{3,4}He$) double ratio and other double ratios based upon the $Y(^3He)/\ Y(^4He)$ ratio, provided $T(^4He^*)$ is normalized like T_o to T_{em} at a single point (T_{em} = 4.4 MeV) [26]. These dependences of T_o and $T(^4He^*)$ are similar because the binding energy differences are comparable for the two cases, and because of the large secondary decay correction for both cases is to the ^4He yields. All calculations which take secondary decay into account will predict identical trends for T_o and $T(^4He^*)$. If measurements reveal strong differences between these two quantities as suggested in ref. [14] for central $Au + Au$ collisions at incident energies above 50A MeV, the resolution of this difference is not likely to be found in equilibrium physics. Rather there must be strong non-equilibrium contributions to ^3He yields, ^4He yields or both.

In summary, we have measured the apparent isotope temperatures for the central and peripheral $Au + Au$ reactions at 35A MeV. For the isotope ratios involving ^3He, ^4He pairs, empirical correction factors that remove the fluctuations in the apparent temperatures measured in the $Au + Au$ system as well as in other systems, provide an easy baseline correction for such effects suitable for temperatures of the order of 4.5 MeV. Sequential decay calculations reproduce these correction factors and show that an identical saturation in the apparent temperatures is expected for the isotope temperatures based upon $^{3,4}He$ pairs as upon a ratio of the ground to the excited state of ^4He. If subsequent measurements do not show these two thermometers to be consistent[14,24], the explanation does not lie in equilibrium physics. Instead there must be strong non-equilibrium contributions to $Y(^3He)$, $Y(^4He)$ or both.

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[26] For experimental comparisons, one could alternatively normalize $T(^4He^*)$ to T_o.

FIGURES

FIG. 1. The apparent temperatures (Eq. 1) for the ten isotope thermometers listed in Table I for central (top) and peripheral (bottom) $Au + Au$ reactions at 35A MeV. Closed circles are data and open squares are predictions from sequential decay calculations. Dashed lines are drawn to guide the eye.

FIG. 2. Raw (left panel) and corrected (right panel) temperatures for three isotope yield ratios as a function of excitation energies for the system $Ar + Ni$ at 95A MeV[10].

FIG. 3. Results of sequential decay calculations. Left Panel: Yield ratios of single isotope pairs. Right panel: T_o (solid line, Eq. 4) and $T(^4He^*)$ (dashed line), the apparent temperature determined from ^4He excited state.

TABLES

TABLE I. List of thermometers with $B > 10$ MeV and the extracted correction factors $\ln \kappa/B$ from experimental data and from sequential decay calculations.

Isotope Ratio	a	B	$(ln\kappa/B)_{expt}$	$(ln\kappa/B)_{calc}$
		(MeV)	(MeV^{-1})	(MeV^{-1})
$^{13,14}C/^{3,4}He$	0.72	12.39	0.0080	0.0166
$^{6,7}Li/^{3,4}He$	2.18	13.32	−0.0051	−0.0015
$^{9,10}Be/^{3,4}He$	0.38	13.76	−0.0840	−0.0813
$^{2,3}H/^{3,4}He$	1.59	14.29	0.0097	0.0114
$^{12,13}C/^{3,4}He$	2.94	15.62	0.0143	0.0047
$^{12,13}B/^{3,4}He$	1.95	15.69	0.0601	0.0445
$^{8,9}Li/^{3,4}He$	1.24	16.51	0.0423	0.0310
$^{11,12}B/^{3,4}He$	1.11	17.20	0.0215	0.0166
$^{1,2}H/^{3,4}He$	5.60	18.4	0.0497	0.0278
$^{7,8}Li/^{3,4}He$	1.98	18.54	0.0265	0.0331

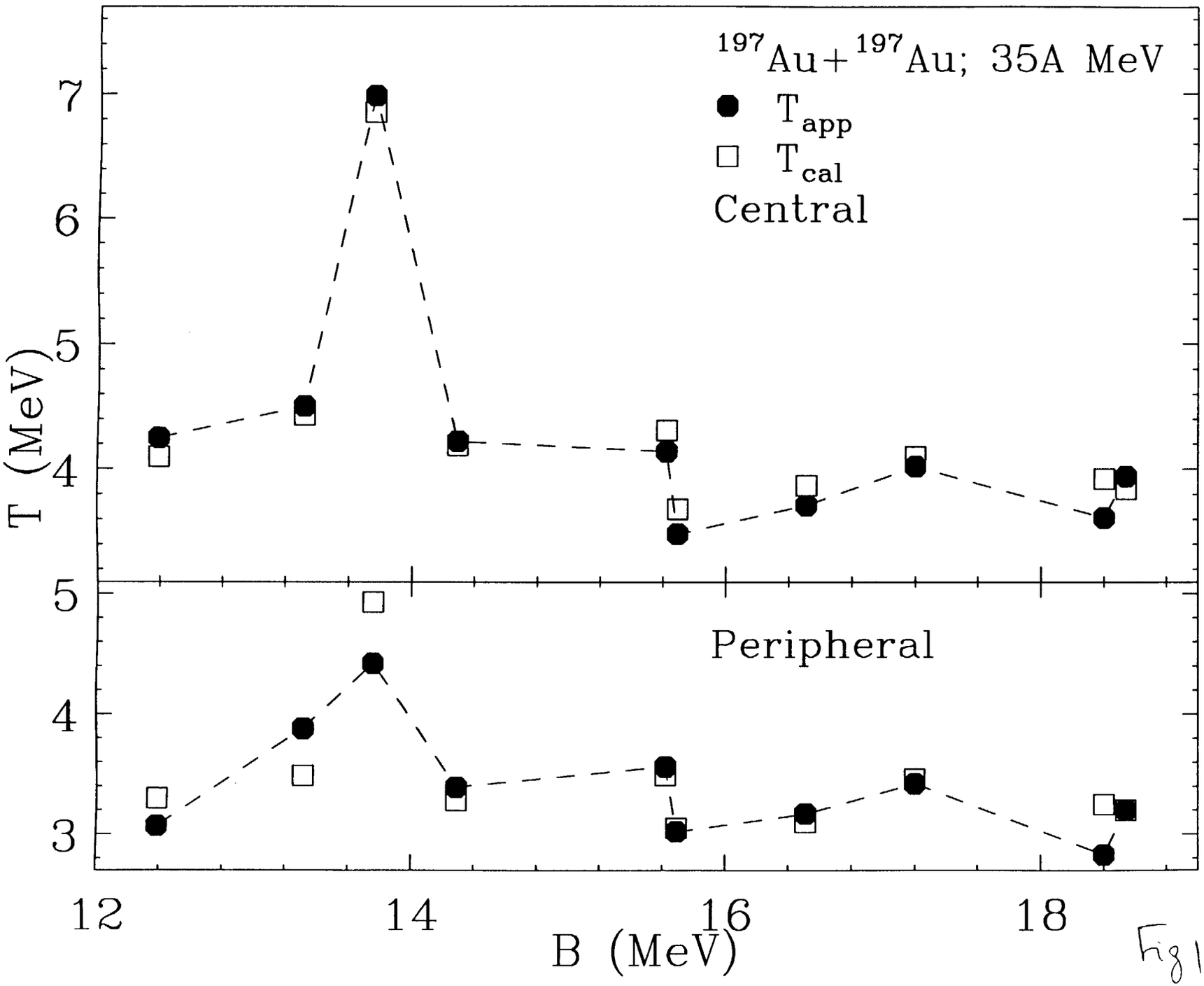
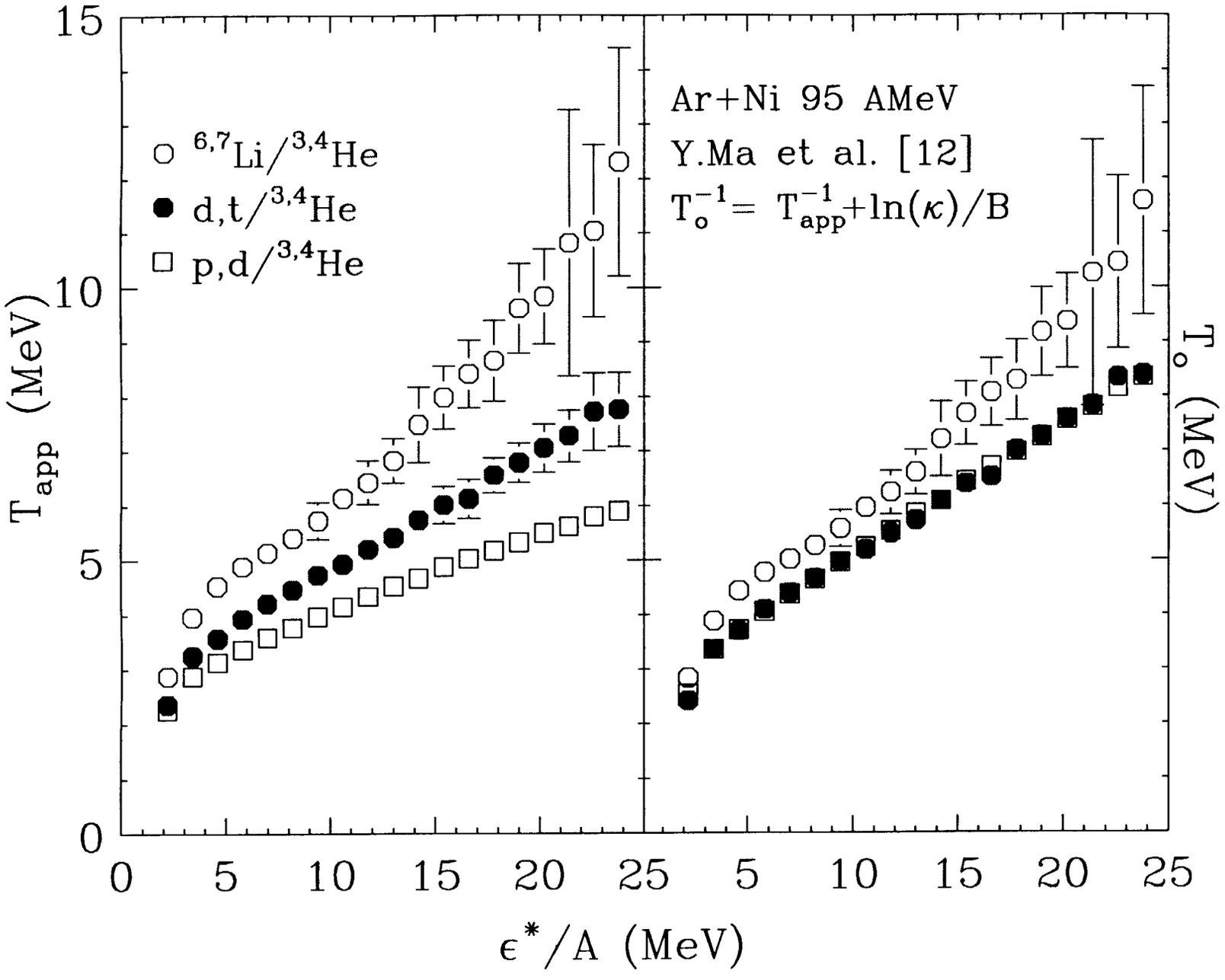

^{197}Au+^{197}Au; 35A MeV
T_{app}
T_{cal}
Central
Peripheral
T (MeV)
B (MeV)
7
6
5
4
3
12
14
16
18

Fig 1


15
10
5
0
0
5
10
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20
25
5
10
15
20
25
T_{app} (MeV)
T_o (MeV)
ϵ^*/A (MeV)
$^{6,7}Li/^{3,4}He$
$d,t/^{3,4}He$
$p,d/^{3,4}He$
Ar+Ni 95 AMeV
Y.Ma et al. [12]
$T_o^{-1} = T_{app}^{-1} + \ln(\kappa)/B$

Fig 2

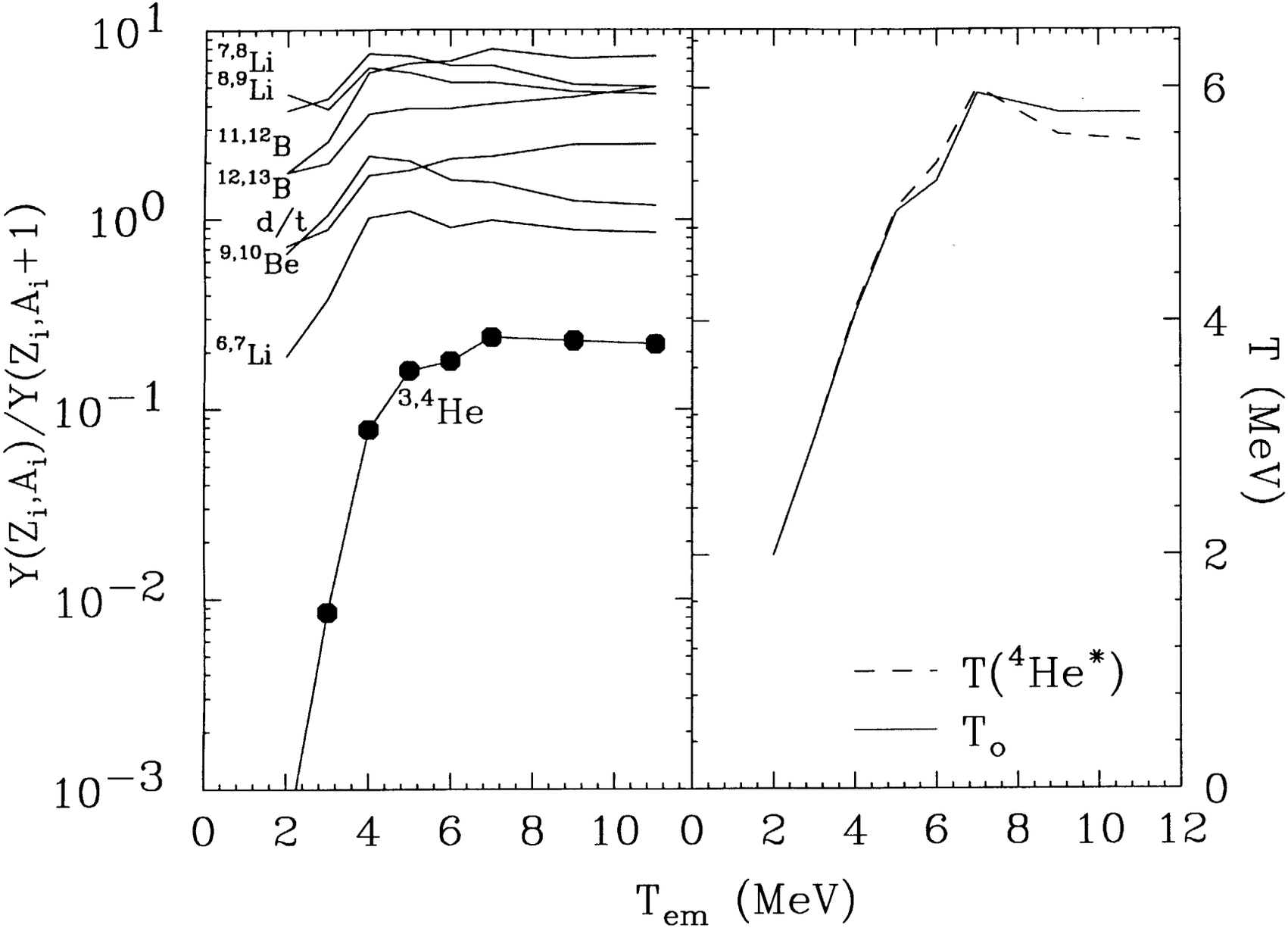
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
$Y(Z_i,A_i)/Y(Z_i,A_i+1)$
^{7,8}Li
^{8,9}Li
^{11,12}B
^{12,13}B
d/t
^{9,10}Be
^{6,7}Li
^{3,4}He
0 2 4 6 8 10
T_{em} (MeV)
$T(^4He^*)$
T_o
0 2 4 6 8 10 12
T (MeV)
0 2 4 6

Fig 3