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Nuclear temperature measurements with helium isotopes

Miniball/Multics Collaboration

H. Xi [a], M.B. Tsang [a], M.J. Huang [a], W.G. Lynch [a], J.D. Dinius [a,1], S.J. Gaff [a,2], C.K. Gelbke [a], T. Glasmacher [a], G.J. Kunde [a,3], L. Martin [a,4], C.P. Montoya [a,5], M. Azzano [b], G.V. Margagliotti [b], P.M. Milazzo [b], R. Rui [b], G. Vannini [b], L. Celano [c], N. Colonna [c], G. Tagliente [c], M. D'Agostino [d], M. Bruno [d], M.L. Fiandri [d], F. Gramegna [e], A. Ferrero [f], I. Iori [f], A. Moroni [f], F. Petruzzelli [f], P.F. Mastinu [g]

[a] *National Superconducting Cyclotron Laboratory and Department of Physics and Astronomy, Michigan State University, East Lansing, MI 48824, USA*

[b] *Dipartimento di Fisica and INFN, Trieste, Italy*

[c] *INFN, Bari, Italy*

[d] *Dipartimento di Fisica and INFN, Bologna, Italy*

[e] *INFN, Laboratori Nazionali di Legnaro, Legnaro, Italy*

[f] *Dipartimento di Fisica and INFN, Milano, Italy*

[g] *Dipartimento di Fisica, Padova and INFN, Bologna, Italy*

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Abstract

Temperatures extracted with the family of (^{3}He, ^{4}He) isotope ratio thermometers, T_{He}, have been studied and cross-checked with temperatures, $T(^4\mathrm{He}^*)$ constructed from excited and ground state populations of ^{4}He. Empirical correction factors provide baseline corrections for sequential decay effects for $T_{\mathrm{He}} < 4.5$ MeV, independent of projectile, target and incident energies. After corrections for fluctuations due to sequential decay, statistical calculations predict that T_{He} and $T(^4\mathrm{He}^*)$ should agree.

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 influ-

[1] Present address: Baker Hill, 655 W. Carmel Dr. Suite 100, Carmel IN 46032, USA.

[2] Present address: TUNL, Duke University, Durham, NC 27708, USA.

[3] Present address: Yale University, New Haven CT 06520, USA.

[4] Present address: Laboratoire de Physique Subatomique, 44070 Nantes Cedex 03 France.

[5] Present address: Merrill Lynch, World Financial Center, New York NY 10281, USA.

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enced 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 thermal and chemical equilibrium directly and are insensitive to collective motion.

Due to the copious production of helium isotopes, many recent temperature measurements extracted from isotope yields utilize the (^{3}He, ^{4}He) isotope pair including the recent extraction of the caloric curve in heavy ion reactions [7]. Thus it is important to understand the family of (^{3}He, ^{4}He) isotope ratio thermometers, T_{He}, and to check for consistencies between different thermometers. At $E/A = 35$ MeV, T_{He} and the excited state temperatures, T_{ex}, measured in the Ar + Au [5] and Au + Au [10] collisions were found to be consistent with each other after correcting for sequential decays. However, for central Au + Au collisions at higher energies ($E/A >$ 50 MeV), increasing differences between T_{He} and T_{ex} were observed [15].

In this paper, we investigate to which degree the effects of sequential decays affect temperatures extracted via the yields of excited states and isotopes. For this purpose, we extend the empirical methods proposed recently for (^{11}C, ^{12}C) and (^{15}O, ^{16}O) thermometers [9] to those involving (^{3}He, ^{4}He). Empirical correction factors are extracted and applied to a wide range of systems. Sequential decay calculations will be used to investigate the relationship between T_{He} and T_{ex}.

In the limit of thermal equilibrium, temperature can be extracted from the relative population of the excited (20.1 MeV) and ground states of ^{4}He.

$$T(^4\mathrm{He}^*) = \frac{-20.1\,\mathrm{MeV}}{\ln\left(Y(^4\mathrm{He}^*)/Y(^4\mathrm{He}^{g.s.})\right)} \qquad (1)$$

Aside from the excited states, temperatures can also be obtained from the ground state yields of (^{3}He, ^{4}He) isotopes and another pair of isotopes according to the expression [6]

$$T_{\mathrm{app}} = \frac{B}{\ln\left(a \cdot R_{\mathrm{app}}\right)} \qquad (2)$$

where $R_{\mathrm{app}} = \frac{Y(A_i,Z_i)/\,Y(A_i+1,Z_i)}{Y(^3\mathrm{He})/\,Y(^4\mathrm{He})}$ is the double yield ratio of the specific pair of isotopes, $B = B(A_j, Z_j) - B(A_j + 1,\ Z_j) + B(^4\mathrm{He}) - B(^3\mathrm{He})$ is the difference between corresponding ground state binding energies, and a is a statistical factor involving the ground state spins and masses of the isotopes [6–9].

Temperatures obtained from either Eq. (1) and Eq. (2) are apparent temperatures. Distortions from secondary decays must be corrected before they can be compared. A recent study of more than 1300 isotope ratio thermometers [9] suggests that secondary decay contributions to the ground state double ratio R_0 can be written as

$$R_{\mathrm{app}} = \kappa R_0 \qquad (3)$$

where κ corrects for sequential decays from higher lying excited states. From Eqs. (2) and (3), T_{app} can be written as [9]

$$\frac{1}{T_{\mathrm{app}}} = \frac{1}{T_0} + \frac{\ln\kappa}{B} \qquad (4)$$

where T_0 is the breakup or emission temperature. The correction term, $\ln\kappa/B$, is small for large B [9]. In practice, only thermometers with $B > 10$ MeV are used. κ depends on the particular double isotope ratio chosen and in principle, depends also on temperature, excitation energy, mass and isospin of the emission source. Which of these dependencies are crucial has to be determined either empirically or from calculations.

Recently, freeze-out temperatures for central Au + Au collisions at 35A MeV have been extracted from excited state yields and also from isotope yields [10,17]. The two methods were found to give consistent results when corrections for secondary decays were taken into account. Sequential decay calculations that best describe these data assumed an emission temperature $T_0 = T_{\mathrm{em}} = 4.4$ MeV [10]. Using Eq. (4), empirical values of $(\ln\kappa/B)_{\mathrm{expt}}$ for ten isotope ratios, all involving ^{3}He and ^{4}He isotopes [10,17], were obtained and listed in Table 1.

Previous studies of different isotope ratio thermometers found little sensitivity in $(\ln\kappa/B)_{\mathrm{expt}}$ to the investigated systems and incident energies [9]. To test if this is also true for the present set of $(\ln\kappa/B)_{\mathrm{expt}}$ values, we have applied Eq. (4) to several reactions, including light systems (Ca + Ni),

Table 1
List of thermometers with $B > 10$ MeV and the extracted correction factors from Eq. (4), $\ln\kappa/B = 1/T_{app} - 1/4.4$. The experimental data, T_{app} and the reference temperature T_{em} are obtained from Ref. [10] and [17] for the central collisions of Au + Au reaction at $E/A = 35$ MeV

Isotope ratio	a	B(MeV)	$(\ln\kappa/B)_{expt}$(MeV^{-1})	T_{app} (MeV)	T_{em} (MeV)
(^{13,14}C, ^{3,4}He)	0.73	12.39	0.0083	4.25	4.4
(^{6,7}Li, ^{3,4}He)	2.18	13.32	$-0.0051(-0.025)$	4.50	4.4 (4.04)
(^{9,10}Be, ^{3,4}He)	0.38	13.76	-0.084	6.98	4.4
(^{2,3}H, ^{3,4}He)	1.59	14.29	0.0097	4.22	4.4
(^{12,13}C, ^{3,4}He)	2.93	15.62	0.0143	4.14	4.4
(^{12,13}B, ^{3,4}He)	1.95	15.69	0.0601	3.48	4.4
(^{8,9}Li, ^{3,4}He)	1.24	16.51	0.0423	3.71	4.4
(^{11,12}B, ^{3,4}He)	1.11	17.20	0.0215	4.02	4.4
(^{1,2}H, ^{3,4}He)	5.60	18.4	0.0496	3.61	4.4
(^{7,8}Li, ^{3,4}He)	1.98	18.54	0.0265	3.94	4.4

heavy systems (Au + Au) and a large range of incident energies (from $E/A = 30$ to 1000 MeV). The results are given in Tables 2, 3, 4 and Fig. 1. The scatter of the corrected temperatures T_0, is much smaller than that for T_{app} as evidenced by the standard deviations (σ^2) for the apparent and corrected temperatures listed in the last rows of Tables 2 and 3.

Table 2 shows the apparent and corrected temperatures obtained in peripheral collisions of the Au + Au at 35A MeV [17] and central and peripheral collisions of the Cu + Xe system at 30A MeV [17]. For the peripheral collisions, temperatures were extracted from projectile-like residues while in central collisions, the emission sources correspond to the equilibrated target-like residues formed in the Cu + Xe collisions. Typically, the temperatures obtained in the Cu + Xe reaction are lower than those obtained in the Au + Au reaction. For example, the mean temperatures for Au + Au are 4.4 MeV (Table 1) and 3.5 MeV (Table 2) for central and peripheral collisions, respectively. For Xe + Cu reaction, the corresponding temperatures are 3.9 and 3.3 MeV (Table 2). The lower temperatures in the lighter system may be related to the incident energy being 5 MeV per nucleon lower. The temperatures extracted

Table 2
Apparent and corrected temperatures for the peripheral collisions of Au + Au reaction at $E/A = 35$ MeV and central and peripheral collisions of Xe + Cu at $E/A = 30$ MeV [17]

Isotope ratio	Au + Au; $E/A = 35$ MeV peripheral collision		Xe + Au; $E/A = 30$ MeV central collision		Xe + Au; $E/A = 30$ MeV peripheral collision	
	T_{app} (MeV)	T_0 (MeV)	T_{app} (MeV)	T_0 (MeV)	T_{app} (MeV)	T_0 (MeV)
(^{13,14}C, ^{3,4}He)	3.07	3.2	3.47	3.57	3.01	3.08
(^{6,7}Li, ^{3,4}He)	3.88	3.8 (3.53)	3.98	3.90 (3.62)	3.64	3.57 (3.34)
(^{9,10}Be, ^{3,4}He)	4.42	3.22	5.42	3.72	4.08	3.03
(^{2,3}H, ^{3,4}He)	3.39	3.51	3.73	3.87	3.14	3.23
(^{12,13}C, ^{3,4}He)	3.56	3.75	3.67	3.87	3.35	3.51
(^{12,13}B, ^{3,4}He)	3.02	3.68	3.14	3.87	2.73	3.26
(^{8,9}Li, ^{3,4}He)	3.17	3.66	3.33	3.86	2.62	2.94
(^{11,12}B, ^{3,4}He)	3.42	3.69				
(^{1,2}H, ^{3,4}He)	2.83	3.29	3.57	4.33	3.25	3.87
(^{7,8}Li, ^{3,4}He)	3.20	3.49	3.77	4.17	3.33	3.65
$\langle T_{He} \rangle$		3.53 (3.49)		3.90 (3.86)		3.30 (3.30)
σ^2	0.22	0.05 (0.04)	0.44	0.05 (0.07)	0.2	0.1 (0.09)

Table 3
Apparent and corrected temperatures for the reaction of Cu + Au at $E/A = 35$ MeV [18] and Ca + Fe, Ni and Ar + Fe, Ni at $E/A = 33$ MeV [13]

Isotope ratio	Cu + Au; $E/A = 35$ MeV		Ca + Fe, Ni and Ar + Fe, Ni $E/A = 30$ MeV	
	T_{app} (MeV)	T_0 (MeV)	T_{app} (MeV)	T_0 (MeV)
(^{6,7}Li, ^{3,4}He)	4.64	4.53 (4.16)	4.27	4.18 (3.86)
(^{9,10}Be, ^{3,4}He)	6.79	4.32	7.32	4.53
(^{2,3}H, ^{3,4}He)	4.00	4.16		
(^{12,13}C, ^{3,4}He)			3.70	3.91
(^{8,9}Li, ^{3,4}He)	3.95	4.74		
(^{7,8}Li, ^{3,4}He)	3.69	4.08		
(^{6,7}Li, ^{11,12}C)			5.28	4.15
(^{12,13}C, ^{11,12}C)			4.18	4.07
$\langle T_{He} \rangle$		4.30 (4.2)		4.17 (4.0)
σ^2	1.6	0.073 (0.085)	2.08	0.05 (0.09)

from central collisions are 0.9 and 0.6 MeV higher for Au + Au and Xe + Cu, respectively, than those obtained from peripheral collisions suggesting only slight temperature dependence on impact parameter.

Table 3 shows the apparent and corrected temperatures for the systems: Ca + Ni, Ar + Ni, Ca + Fe, Ar + Fe collisions at 33A MeV [13] and Cu + Au system at 35A MeV [18]. The first set of data includes measurements from isotope yields of ^{11}C and ^{12}C. Thus we obtain a valuable additional cross-comparison of thermometers belonging to the (^{11}C, ^{12}C) and (^{3}He, ^{4}He) families using $(\ln\kappa/B)_{expt}$ values listed in Table 1 and Ref. [9]. The corrected temperatures obtained from (^{6,7}Li, ^{11,12}C) and (^{12,13}C, ^{11,12}C) are in good agreements with temperatures obtained from (^{6,7}Li, ^{3,4}He), (^{9,10}Be, ^{3,4}He) and (^{12,13}C, ^{3,4}He).

Table 4 contains the apparent and corrected temperatures obtained with the (^{6,7}Li, ^{3,4}He), (^{2,3}H, ^{3,4}He) and (^{1,2}H, ^{3,4}He) isotope ratios in the impact parameter gated Au + Au collisions at 1000A MeV [14].

Of the ten isotope ratios listed in Table 1, the two most common ratios used are (^{2,3}H, ^{3,4}He) and (^{6,7}Li, ^{3,4}He) isotope pairs. In particular, (^{6,7}Li, ^{3,4}He) played a crucial role in the extraction of the caloric curve in Ref. [7]. In all cases, the temperatures constructed with (^{6,7}Li, ^{3,4}He) isotopes, T_{HeLi}, tend to be consistently higher than the temperatures constructed with (^{2,3}H, ^{3,4}He) isotopes, T_{HeH}, even after corrections. The disagreement between corrected T_{HeLi} and T_{HeH} can be more clearly seen in Fig. 1 for a large range of excitation energies. The figure shows temperatures extracted for Ar + Ni collisions at 95A MeV [12] using isotope ratios of (^{6,7}Li, ^{3,4}He), (^{2,3}H, ^{3,4}He) and (^{1,2}H, ^{3,4}He) [6]. Before correction (left panel), the differences between different isotope ratio temperatures increase with excitation energy. After correction (right panel), the isotope ratio temperatures from (^{2,3}H, ^{3,4}He) and (^{1,2}H, ^{3,4}He) collapse onto one another, but the corrected T_{HeLi} (open circles) is consistently higher. The discrepancy can be removed by using a value of $\ln\kappa/B$ which is slightly different (-0.025 MeV^{-1}) from that (-0.005 MeV^{-1}) extracted from the calibration reaction, Au + Au at $E/A = 35$ MeV (see solid line). Indeed some slight dependence of $\ln\kappa/B$ on reaction persist for other ratios as well, illustrating the limitations of the present empirical correction technique. Corrected T_{HeLi} obtained using the empirical value of -0.025 MeV^{-1} are shown in parenthesis in Table 1–4.

Based on the results of the systems studied, it appears that the major source of discrepancy between different isotope temperatures is the lack of adequate corrections for secondary decay. Over the range of projectile and target combination and incident energy investigated in the present work, the

[6] The extracted temperatures from isotope ratio (^{1,2}H, ^{6,7}Li) in Ref. [12] were not included because its small B value renders it unsuitable for temperature extraction.

Table 4
Apparent and corrected temperatures for the reaction of Au + Au at $E/A = 1000$ MeV as a function of $Z_{\rm bound}$ [14]

Isotope ratio	$Z_{\rm bound} = 0$–10		$Z_{\rm bound} = 20$–30		$Z_{\rm bound} = 40$–50		$Z_{\rm bound} = 60$–70	
	$T_{\rm app}$ (MeV)	T_0 (MeV)	$T_{\rm app}$ (MeV)	T_0 (MeV)	$T_{\rm app}$ (MeV)	T_0 (MeV)	$T_{\rm app}$ (MeV)	T_0 (MeV)
(^{6,7}Li, ^{3,4}He)	8.75	8.38 (7.18)	6.25	6.06 (5.4)	5.25	5.11(4.53)	4.0	3.92 (3.64)
(^{2,3}H, ^{3,4}He)	5.78	8.11	4.38	5.60	3.80	4.68	3.3	3.95
(^{1,2}H, ^{3,4}He)	6.67	7.13	5.25	5.53	4.40	4.60	3.75	3.89

extracted $(\ln\kappa/B)_{\rm expt}$ values provide first order corrections to the apparent temperature using Eq. (4).

Recent studies show that temperatures extracted from excited states such as ^{4}He, ^{5}Li and ^{8}Be are similar over all incident energies [15]. On the other hand, $\langle T_{\rm He}\rangle$ increases with incident energies. Of particular concern is the disagreement between $\langle T_{\rm He}\rangle$ and $T(^4{\rm He}^*)$ at high energies. Intuitively, one expects $\langle T_{\rm He}\rangle$ to behave similar to $T(^4{\rm He}^*)$ because the energy difference between the excited and ground states of ^{4}He is comparable to the binding energy difference of ^{3}He and ^{4}He. Moreover, both thermometers suffer from the copious production of the alpha particles from sequential decay of heavier nuclei.

To study the behavior of these two families of thermometers, we use the statistical calculations of Ref. [8] which reproduce experimental results of Ref. [10]. Before sequential decay, the primary distributions were obtained by using a standard statistical model based on the Hauser Feshbach formalism of evaporation from a heavy residue [8]. Fig. 2 shows the results of the calculations if the excited daughter nuclei decay from only the discrete unbound states tabulated in Ref. [19] (left panel) or from both discrete and continuum states (right panel). These

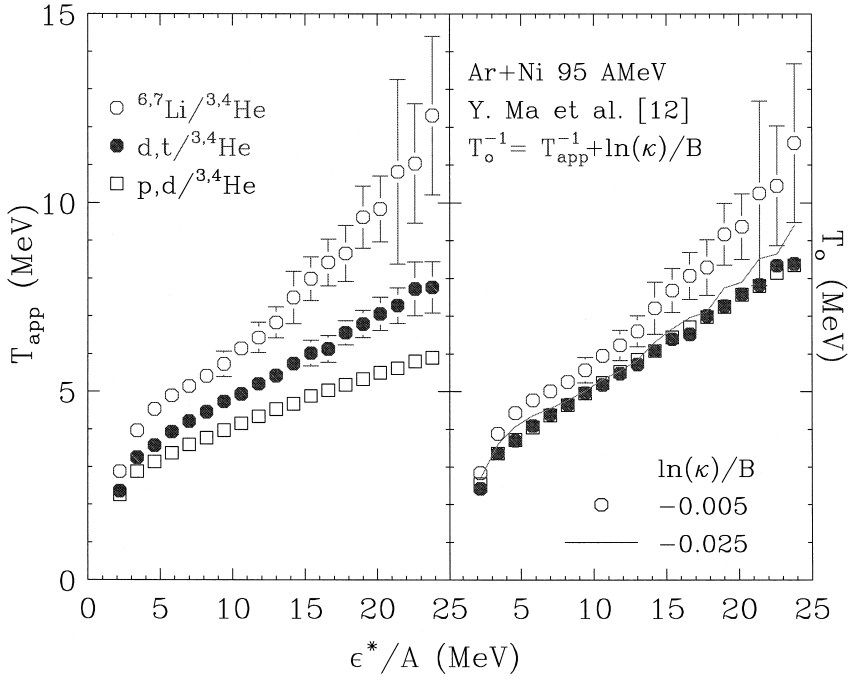

Fig. 1. Raw (left panel) and corrected (right panel) temperatures for three isotope yield ratios as a function of excitation energies for the system Ar + Ni at 95A MeV [12] (see footnote 6).

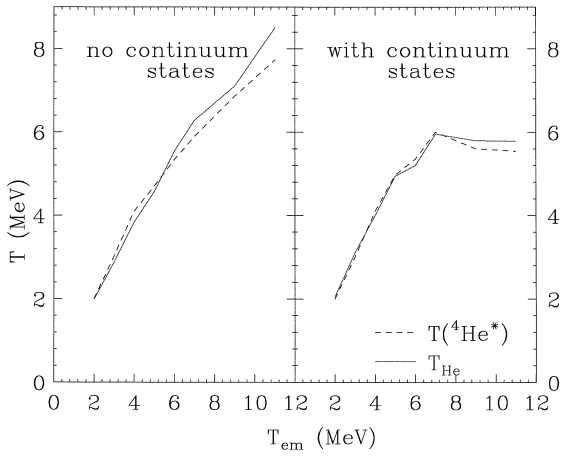

Fig. 2. $\langle T_{\mathrm{He}} \rangle$ (solid line) and $T(^4\mathrm{He}^*)$ (dashed line) obtained from statistical decay calculations. The sequential decays include only discrete states (left panel) and discrete states as well as continuum states (right panel).

calculations were performed from $T_{\mathrm{em}} = 2$–11 MeV in 1 MeV steps. At each emission temperature, ten apparent temperatures were extracted from the predicted ground state yields using the same isotope pairs listed in Table 1. Values of T_0 were then extracted using the $(\ln \kappa/B)_{\mathrm{expt}}$ values and Eq. (4). For each value of T_{em}, the average value of T_0 is denoted as $\langle T_{\mathrm{He}} \rangle$, shown as solid lines in Fig. 2. $T(^4\mathrm{He}^*)$ are also evaluated from the same calculations using Eq. (1) and plotted as dashed lines in Fig. 2. Since $\langle T_{\mathrm{He}} \rangle$ is normalized to 4.4 MeV via the use of $(\ln \kappa/B)_{\mathrm{expt}}$ values listed in Table 1, $T(^4\mathrm{He}^*)$ is also normalized at the same temperature using similar procedure described by Eqs. (3) and (4).

Consistent with previous studies [7,8,12,20], the apparent isotope temperatures increase monotonically with the input temperature when continuum states were not included in the secondary decay. With inclusion of continuum states, $\langle T_{\mathrm{He}} \rangle$ attains an asymptotic value of about 6 MeV when the emission temperature is larger than 7 MeV. Details of this saturation depend on the detailed assumptions on the population of continuum states and input parameters to the calculations. In both calculations, $(\ln \kappa/B)_{\mathrm{expt}}$ allow a reduction of fluctuations of different thermometers and provide a first order correction to the sequential decay. However, above 5 MeV, the precise temperature dependence of $\langle T_{\mathrm{He}} \rangle$ can be obtained only from reliable sequential decay calculations. When continuum states were included in the decay, the insensitivity of the yield ratios to T_{em} precludes any determination of the temperature dependence of $\ln \kappa/B$ above 6 MeV.

Independent of whether continuum states were included in the calculations or not, the sequential decay calculations predict nearly identical trends for $\langle T_{\mathrm{He}} \rangle$ and $T(^4\mathrm{He}^*)$. Therefore, the significant differences observed between $\langle T_{\mathrm{He}} \rangle$ and $T(^4\mathrm{He}^*)$ at high incident energies [15] cannot be attributed to sequential feeding but must be due to the primary productions of particles. Primary production mechanisms which can lead to differences in extracted values of $\langle T_{\mathrm{He}} \rangle$ and $T(^4\mathrm{He}^*)$ can, for example, arise from excluded volume effects [20] or alternatively, from a sequential rather than instantaneous freeze-out scenario in which different particles (or states) freeze out at different densities or temperatures [21–23].

In summary, for the isotope ratios involving (^{3}He,^{4}He) pairs, empirical correction factors that remove the fluctuations in the apparent temperatures measured in the Au + Au system, provide an easy baseline correction for other systems suitable for temperatures of the order of 4.5 MeV. The apparent temperatures extracted from the isotope ratios involving (^{3}He, ^{4}He) and the ratio of the ground state to the excited state of ^{4}He should be affected by sequential decays in the same manner. Any significant discrepancy between these two thermometers [15] must be attributed to the primary production of ^{3}He and/or ^{4}He. Further investigations will have to clarify whether other factors such as excluded volume effects or sequential freeze-out scenarios can provide an internally consistent description of the measured temperatures from different thermometers.

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