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Abstract

Light fragments (d, t, ^{3}He, ^{4}He) were measured for central collisions of ^{112}Sn + ^{112}Sn and ^{124}Sn + ^{124}Sn at E/A = 40 MeV. While individual isotope ratios depend strongly on the neutron-to-proton ratio of the entrance channel, the double ratio $R_{H\text{-}He} = [Y(d)Y(^4He)]/[Y(t)Y(^3He)]$ shows no such sensitivity. Within the assumptions of the Albergo thermometric technique, this independence is consistent with the attainment of full chemical equilibrium for each reaction at the same common temperature. However, the same independence is also predicted by calculations based on emission from an expanding emitting source, where the yield for the final double ratio is not obtained at a single well defined source temperature.

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Studies of the thermodynamic properties of nuclear matter require accurate methods of temperature determination. Double-ratios of isotope yields which cancel out chemical potential effects offer a particularly promising technique of temperature determination, known as the Albergo-method [1-9]. Recent applications of this technique suggested a relationship between excitation energy per nucleon and temperature which bears a remarkable similarity to the caloric curve of boiling water [2]. The interpretation of this "caloric curve" [10,11] as well as the accuracy of the temperature scale employed remain controversial [3-9]. The accuracy of such "caloric curve" determinations depends on whether statistical equilibrium at a single temperature is a valid interpretation of the experimental data. In previous papers the distortions caused by feeding from high-lying particle unbound states have been examined for their influence on the determination of an equilibrium temperature [3-9].

In this paper, we perform an experimental test of a condition necessary for the validity of the Albergo method and examine, by model calculations, whether this condition is a sufficient test of the validity of the method. Specifically, we measure the double ratio of hydrogen and helium isotopic yields, $R_{H\text{-}He}$ = $[Y(d)Y(^4He)]/[Y(t)Y(^3He)]$, for central collisions of $^{112}Sn + ^{112}Sn$ and $^{124}Sn + ^{124}Sn$ at E/A = 40 MeV. These two systems are energetically similar, but have very different proton-to-neutron ratios. The validity of the Albergo formula [1], $T_{H\text{-}He} = 14.26/\ln(1.39R_{H\text{-}He})$ MeV, requires that the double ratio $R_{H\text{-}He}$ be the same for both reactions. We find that the data are consistent with this condition, but that is insufficient to demonstrate the existence of full statistical equilibrium at a well defined freeze-out temperature.

The experiment was performed at the National Superconducting Cyclotron Laboratory at Michigan State University. The areal density of the targets was 5 mg/cm^2. Charged particles were measured with 280 plastic scintillator - CsI(Tl) phoswich detectors of the Miniball/Miniwall array [12,13] mounted in the Superball scattering chamber [14]. The charged particle array covered approximately 90% of 4π and provided isotopic resolution for H and He nuclei and elemental resolution for intermediate mass fragments (IMF) with $3 \leq Z \leq 20$. Results on IMF emission and on reaction filters for this experiment are published elsewhere [15,16]. The following analysis focuses on central events defined by a gate on the cross section corresponding to the top 10 percent of the charged-particle multiplicity distribution, $b/b_{max} < 0.3$ [15,16]. To further suppress possible contributions from projectile and target-like spectator sources, we restrict the analysis to particles emitted at large center-of-mass angles, 75° $\leq\theta_{CM}\leq 105°$, and apply a software threshold of $E_{CM}/A \geq 5$ MeV in the center-of-mass system.

The open and solid circular points in Fig. 1 show the measured isotopic yield ratios [17], d/t and $^3He/^4He$, and the double ratio, $R_{H\text{-}He}$, for central ^{112}Sn + ^{112}Sn and ^{124}Sn + ^{124}Sn collisions, respectively. For both reactions, ^{112}Sn + ^{112}Sn and ^{124}Sn + ^{124}Sn, the measured double ratio is the same, $R_{H\text{-}He}$ = 10, within experimental errors. Thus the isotope double ratio is independent of the isospin of the system as is required for consistency with equilibrium that is necessary for fragmentation models. This value for the $R_{H\text{-}He}$ double ratio is obtained from the two isotope ratios, d/t and $^3He/^4He$, which both depend strongly on the proton-to-neutron ratio of the reaction involved. Both the d/t and the $^3He/^4He$ isotope ratios are about 40% greater for the ^{112}Sn + ^{112}Sn reaction than for ^{124}Sn + ^{124}Sn. As a consequence, the $R_{H\text{-}He}$ double ratio has the same value for both systems.

This confirmation of the insensitivity of the $R_{H\text{-}He}$ double ratio to the N/Z ratio of the emitting source is, however, insufficient to ensure the existence of a well defined freeze-out temperature. To illustrate this point, we performed calculations with the expanding emitting source (EES) model of ref. [18]. We assumed the equilibrium source starts from rest with an initial excitation energy of E^*/A=8 MeV and T=11.16 MeV. This particular value of E^*/A corresponds to roughly 80% of the available energy in the center of mass system [19]. The sensitivity to the unknown mass of the sources was assessed by investigating two limiting cases, corresponding to initial sources containing all nucleons from target and projectile (denoted as ^{224}Fm and ^{248}Fm) or, alternatively, only one-half the total number of protons and neutrons (denoted as ^{112}Sn and ^{124}Sn).

Predictions of the EES model are shown by rectangular symbols in Fig. 1, where calculated values are shown for both the individual d/t and the $^3He/^4He$ ratios and also for the double ratio $R_{H\text{-}He}$. Solid (open) symbols indicate the initial neutron-to-proton ratio of N/Z = 1.48 (1.24). The vertical size of the rectangular symbols indicates the variation of the model prediction for the two extreme source sizes. (Since the d/t ratio is nearly independent of source size, the rectangular symbols shrink to lines, with the N/Z = 1.48 case having the lower values.) The model provides predictions for both primary yields and additional contributions from the decay of low-lying resonances of He, Li, and Be isotopes. The predicted contributions from the sequential feeding to the final particle yields are listed in Table 1 as a percentage of the primary yield. The model predictions for the respective ratios from both the primary (p) and final (f) yields are indicated by the same symbols and compared with the experimental values indicated by circles. The model predicts significant feeding contributions to all isotopes of light nuclei. For the case of ^{4}He, the predicted final yield is dominated by contributions from sequential decay.

Most remarkably, the EES model predicts that the $R_{H\text{-}He}$ double-ratio is very insensitive to the N/Z ratio of the emitting source and only slightly sensitive to its size, see right-hand column of Fig. 1. This insensitivity to source size is predicted for the double ratios of both primary and final particle yields. Consistent with previous findings, however, the magnitude of the calculated double ratio is strongly altered by sequential feeding from particle unbound decays [4-9]. Since the yields of particle unbound primary fragments and their subsequent decay have not been measured in this experiment, the excellent agreement between measured and predicted final $R_{H\text{-}He}$ double-ratios must be viewed with caution and could be fortuitous.

The problem of sequential feeding and the associated uncertainties of temperature determinations have long been recognized and remain a subject of ongoing research [3-9]. Even in the absence of sequential feeding, however, the extraction of emission temperatures from double-ratios of isotopes can be problematic, regarding the existence of a single freeze out temperature. This will be the case if the time scale of particle emission is commensurate with that for cooling and expansion [20]. Since the (EES) model is based on this assumption, we next illustrate this point using calculations with this model.

Fig. 2 shows the predicted time-dependence of light particle emission rates and instantaneous temperatures for the sources ^{224}Fm (dashed curves) and ^{248}Fm (solid curves) initially at $E^*/A = 8$ MeV. As expected, both sources are predicted to exhibit rather similar (though not identical) temperature curves with a local maximum at $t \approx 150$ fm/c caused by a maximum in the density oscillation of the source (lower right panel). With the exception of ^{4}He, the predicted light-particle emission rates exhibit a similar time dependence including a maximum at $t \approx 150$ fm/c, with the absolute rates depending on the N/Z ratio of the initial source. In contrast, the ^{4}He rates exhibit a distinctly different time dependence with a pronounced maximum at $t \approx 60$ fm/c (plus some less interesting damped oscillations at later times). The EES model predicts an enhanced emission of strongly bound ^{4}He nuclei and IMFs (at $t \approx 60$ fm/c) relative to nucleons and the other light particles when the source has expanded to a low density minimum. As a consequence, light particles (including ^{3}He) sample the temporal evolution of the expanding source with different time-dependent weights than do IMFs and ^{4}He nuclei. Within the EES model, double ratios involving (time-integrated) yields of ^{3}He and ^{4}He nuclei therefore provide an "apparent temperature", but this value cannot be related to the temperature at some average freeze-out time, because ^{3}He and ^{4}He nuclei are preferentially emitted at different stages of the reaction [20,21].

The dashed and solid curves in Fig. 3 depict the calculated time evolution of the predicted cumulative $R_{H\text{-}He}$ double-ratios for the sources ^{224}Fm and ^{248}Fm, respectively. Note, only the asymptotic value, $t \to \infty$, is accessible to experiment. (Sequential decays are neglected in these calculations.) The predicted double ratio increases until about $t \approx 100$ fm/c and changes little thereafter. At all times the cumulative $R_{H\text{-}He}$ double-ratio is predicted to be virtually independent of the N/Z-ratio of the source.

Just as for the Albergo method, with full statistical equilibrium (a condition not reached in the EES model), the instantaneous rates and branching ratios contain factors which depend on binding energies, temperatures, Coulomb energies (barriers), and the chemical potentials for protons and neutrons in the source. Coulomb barrier effects are largely canceled for ratios of rates involving isotopes of the same elements. Furthermore, double ratios of rates, as with the Albergo formula, provide cancellation of the influence of chemical potentials, and provide values determined primarily by binding energies, temperatures, and weights due to spin degeneracies. The $R_{H\text{-}He}$ double-ratios of the instantaneous emission rates, are also shown in Fig. 3 by the dot-dashed (^{224}Fm) and dotted (^{248}Fm) curves. These curves oscillate in accordance with the underlying temperature curves (Fig. 2), with a slightly slower period for the heavier source -- an effect already visible in the individual emission rates shown in Fig. 2.

The $R_{H\text{-}He}$ double-ratio of instantaneous emission *rates* does, indeed, reflect the instantaneous temperature of the emitting source. This is illustrated in Fig. 4 for the source ^{248}Fm. The dotted curve shows the temperature obtained by applying the Albergo formula [1] to the double ratio of instantaneous emission *rates* (not yields) predicted by the EES model, and the dot-dashed curve shows the instantaneous temperature of the model calculation. The two curves track quite well. For comparison, the solid curve shows the temperature determined by means of the Albergo formula from the cumulative yield of particles emitted prior to time t. The experimentally accessible value ($t \rightarrow \infty$) represents a complicated integral over the history of the system and reflects neither the initial temperature of the source, nor its temperature at the low density phase where IMF production is predicted to be maximal.

In summary, we have investigated the emission of light particles in central collisions of $^{112}Sn + ^{112}Sn$ and $^{124}Sn + ^{124}Sn$ at E/A = 40 MeV and confirmed the insensitivity of the R_{H-He} double-ratio to the neutron-to-proton ratio of the emitting source predicted by grand canonical ensembles. This insensitivity is, however, also predicted by the EES model which incorporates time-dependent cooling by expansion and evaporation, plus feeding from particle unbound states of primary emitted fragments. Unless a near-instantaneous freeze-out is ascertained from other observables, the connection between double-ratios of isotopes and a well-defined (average) temperature of the system can be complicated by the fact that different particle species may be emitted at different stages of the reaction. In particular, the EES model predicts that ^3He and ^4He nuclei are preferentially emitted at different stages of the reaction, adding a further complexity to the meaning of "temperatures" extracted from double-ratios of isotopes involving ^3He and ^4He.

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Table 1.

Contributions (as percentage of the primary yields) from sequential decays of particle unbound primary fragments calculated for the sources ^{224}Fm and ^{248}Fm, initially at $E^*/A = 8$ MeV.

particle	$^{112}Sn + ^{112}Sn$	$^{124}Sn + ^{124}Sn$
d	13%	10%
t	11%	8%
^{3}He	53%	67%
^{4}He	141%	145%

Figure Captions

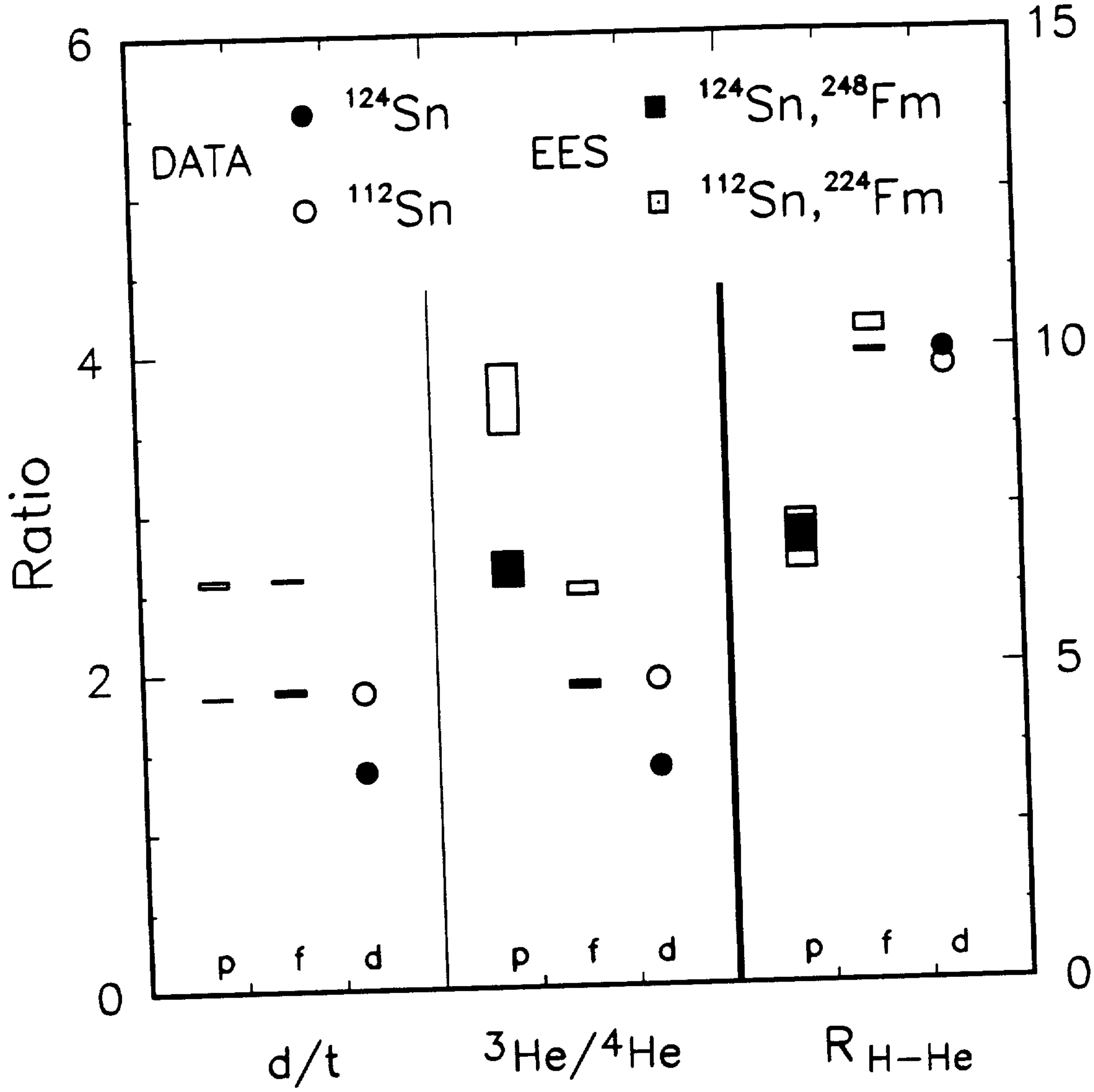
Fig. 1: Single yield-ratios (left panel), d/t and ^{3}He /^{4}He (times 10), and double-ratio $R_{H\text{-}He}$ (right panel) for central $^{112}Sn + ^{112}Sn$ (open symbols) and $^{124}Sn + ^{124}Sn$ (solid symbols) collisions at E/A=40 MeV. Experimental data (d) are shown as circles. Rectangular symbols represent predictions of the EES model for sources with $E^*/A = 8$ MeV. The vertical size of the symbols depicts the difference in prediction for a source containing all (upper edge) or only one-half (lower edge) of the protons and neutrons contained in the combined projectile and target system. Theoretical predictions for primary and final particle ratios are labeled p and f.

Fig. 2: Temporal evolution of p, d, t, ^{3}He, and ^{4}He emission rates and source temperatures predicted by the EES model. Dashed and solid curves depict calculations for initial sources ^{224}Fm and ^{248}Fm, respectively, with $E^*/A = 8$ MeV.

Fig. 3: $R_{H\text{-}He}$ double-ratios of instantaneous emission *rates* predicted by the EES model for the initial sources ^{224}Fm (dot-dashed curve) and ^{248}Fm (dotted curve) with $E^*/A = 8$ MeV. The dashed (^{224}Fm) and solid (^{248}Fm) curves show the cumulative $R_{H\text{-}He}$ double-ratios for the yield of particles emitted prior to time t.

Fig. 4: Comparison of instantaneous source temperature (dot-dashed curve) to temperature extracted by applying the Albergo formula to the instantaneous

emission *rates* (dotted curve) and to the cumulative yield of particles emitted prior to time t (solid curve) for the initial source ^{248}Fm with $E^*/A = 8$ MeV.



DATA
^{124}Sn
^{112}Sn
EES
$^{124}Sn, ^{248}Fm$
$^{112}Sn, ^{224}Fm$
Ratio
p f d
p f d
p f d
d/t
$^3He/^4He$
R_{H-He}

Fig 1

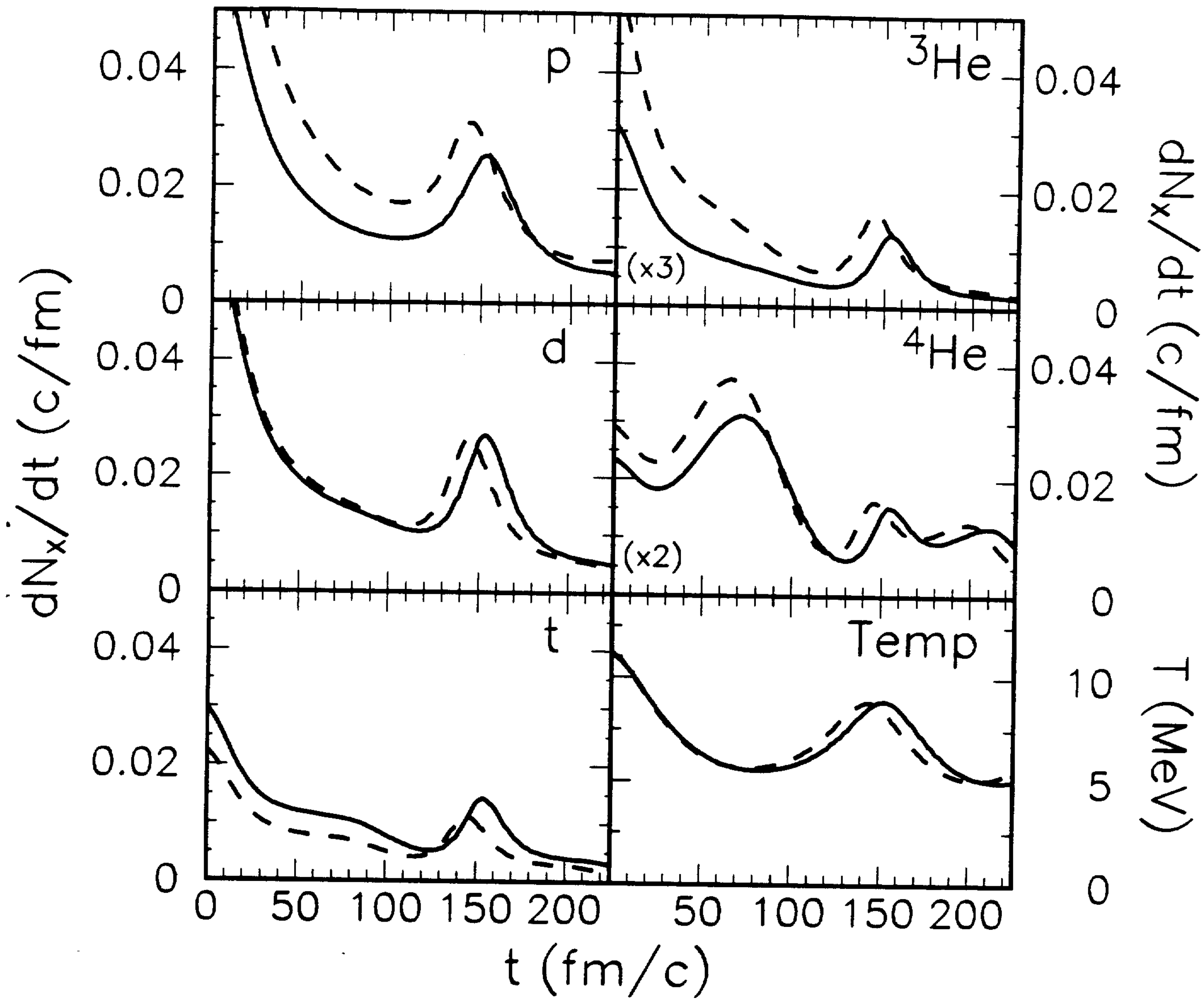

p
³He
d
⁴He
t
Temp
(x3)
(x2)
0.04
0.02
0
10
5
0 50 100 150 200
50 100 150 200
dNx/dt (c/fm)
T (MeV)
t (fm/c)

Fig2

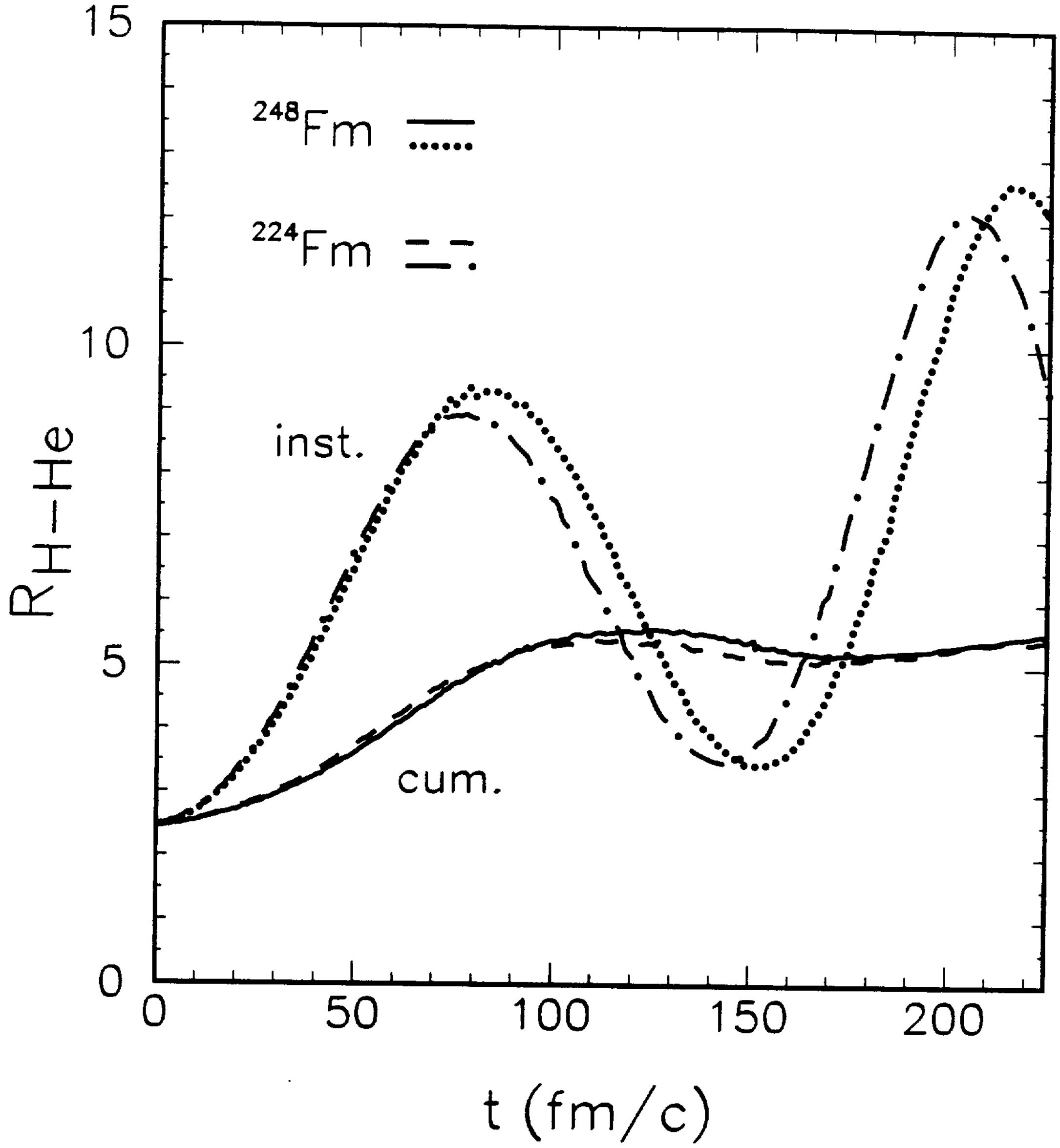
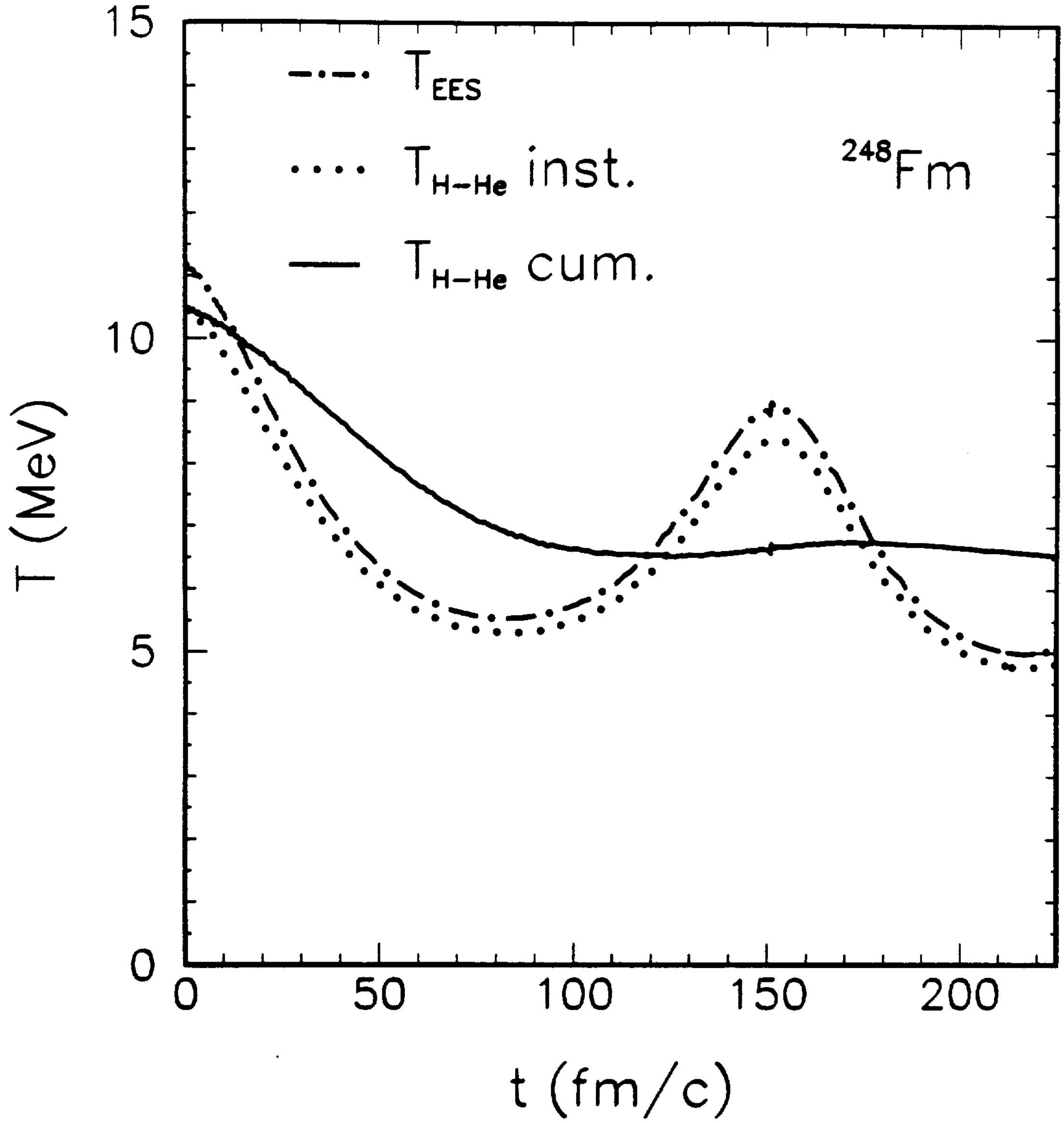


Fig 3



T_{EES}
T_{H-He} inst.
T_{H-He} cum.
^{248}Fm
15
10
5
0
0
50
100
150
200
T (MeV)
t (fm/c)

Fig 4