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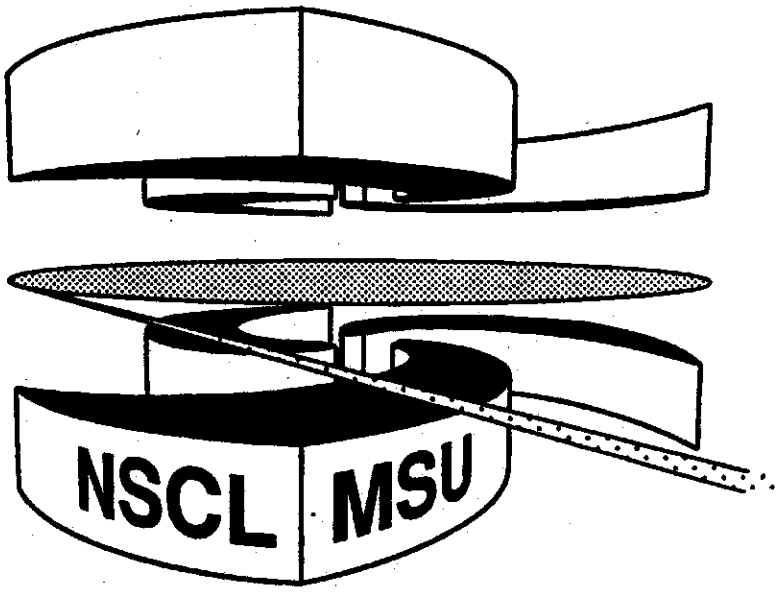

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Examining the Cooling of Hot Nuclei

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Abstract

Energy spectra have been measured for Helium and Hydrogen isotopes emitted from highly excited residues produced in central ^{129}Xe+^{nat}Cu collisions at E/A=30 MeV. The observed differences between the spectra for ^{3}He and ^{4}He nuclei can be attributed to the time dependent evaporative cooling of the residues. This cooling dynamics is also reflected in a characteristic dependence of isotope ratios on the kinetic energy of the emitted particles in reasonable agreement with present evaporative models.

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Information about the thermal properties of highly excited nuclear systems can be extracted from the properties of particles emitted during their decay [1-6]. This extraction depends intimately upon the assumed timescale for disintegration. At low excitation energies, the timescale is long and the system decays sequentially, emitting one particle after another [4-6]. At high excitation energies, the timescale may be short enough to justify the utilization of instantaneous multiparticle decay models [1-3]. Extraction of the thermodynamic properties of nuclei and nuclear matter differs depending upon whether processes are assumed to be sequential or simultaneous. The determination of the timescale for emission and its influence on the properties of the decaying system is therefore essential [7].

Measurements of correlations between particles at small relative momentum have provided reasonable estimations of decay timescales [8-12]. The observation of a non-negligible decay timescale, however, does not necessarily imply a cooling between successive emissions and a consequent failure of simultaneous decay models if the decay timescales are shorter than the equilibration time [7]. Instead, direct observations of the variation of temperature with time are needed. Here, we propose using isotope ratio thermometers to probe the cooling of highly excited nuclear systems and successfully test this approach by studying the decay of a highly excited nucleus formed in the Xe+Cu collision.

Previous studies of Xe+Cu collisions at 30A MeV have confirmed that emission in central collisions proceeds via both equilibrium and preequilibrium mechanisms[11]. These investigations also suggest that particles emitted in the forward angles are dominated by the statistical decay of equilibrated target-like residues [11]. Comparisons to the sequential Expanding Evaporating Source (EES) model [5] and to the instantaneous microcanonical Berlin Multifragmentation Model (BMM) [2] were given in ref. [11] for excitation energies, masses, charge and expansion velocities provided by one-body Boltzmann Nordheim Vlasov (BNV) transport [13] calculations. Reproduction of the measured fragment emission velocities and small relative velocity correlations between two intermediate mass fragments (IMF's $3 \leq Z \leq 9$) was obtained for the sequential EES model and not the simultaneous BMM model. The essential assumption of the EES model

that the system cools and equilibrates between each sequential decay was not tested, however.

Evidence for the significance of cooling between successive emissions can be obtained by comparing the relative isotopic abundance of higher energy particles emitted early in the decay to the relative isotopic abundance of lower energy particles emitted later after the system has cooled. To test the cooling assumption of the EES model, we have measured the hydrogen and helium energy spectra of the inverse kinematic reaction of Xe+Cu collisions. The experiment was performed by bombarding a 5 mg/cm^2 natural Cu target with the 30A MeV ^{129}Xe beam of the National Superconducting Cyclotron Laboratory at Michigan State University. Isotopically resolved light charged particles and IMF's for Z≤6 were detected at $3°\leq\theta_{lab}\leq23°$ in the Multics array of 44 gas-Si-CsI telescopes[14]. Light particle energy calibrations accurate to 2% were obtained by irradiating each telescope with ^{228}Th and ^{244}Cm α sources and by measuring with low intensity direct α particle beams[15]. Charged particles were detected at $23°\leq\theta_{lab}\leq160°$ by 166 fast plastic-CsI phoswich detectors of the MSU Miniball array[16] and used to assign the impact parameters for the collisions, following ref. [15]. By gating on events with value for the total charged particle multiplicity in the highest 10% of the multiplicity distribution, energy spectra for central collisions were obtained at forward angles $3°\leq\theta_{lab}\leq23°$ for this "reverse kinematics" Xe+Cu reaction, corresponding to center of mass angles less than 70°.

Energy spectra, obtained in the c.m. frame assuming a center of mass velocity of v_{cm} = 0.185 c [17], are shown in Fig. 1 for Hydrogen (upper panel) and Helium isotopes (middle panel). All four spectra display a broad maximum at the Coulomb barrier and decrease monotonically at higher energies. The shapes of the spectra for the two Hydrogen isotopes are rather similar. In contrast, the spectral shapes for the two Helium isotopes differ, consistent with statistical expectations that the ratio of the yield of weakly bound ^{3}He's over strongly bound ^{4}He's will be larger for high energy particles emitted from the hot system than for lower energy particles emitted after the system has cooled. This tendency is displayed more clearly in the lower panel of Fig. 1, where the ^{3}He spectrum has been normalized to coincide with the ^{4}He spectrum at E_{CM}=20

MeV (open and closed circles). Similar differences between ^{3}He and ^{4}He spectra have been reported for other reactions as well [18]. For comparison, the ^{2}H sepectra is normalized to ^{3}H spectra at E_{CM}=10 MeV (open and closed squares). In contrast to the Helium isotope, the energy spectra of the hydrogen isotope have nearly identical shapes.

To examine the cooling trend quantitatively, we explored a double isotope ratio $R_{H\text{-}He}$ [19],

$$R_{H\text{-}He}(E_{K0}) = \{Y(^2H, E_{K0})/Y(^3H, E_{K0})\}/\{Y(^3He\ E_{K0})/Y(^4He, E_{K0})\}, \qquad (1)$$

where $Y(^AX)$ is the yield for isotope ^AX, $E_{K0} = E_{cm,i} - V_i$ is the kinetic energy of the emitted particle in the c.m. system prior to Coulomb acceleration, $E_{cm,i}$ is the observed c.m. kinetic energy, and V_i is the Coulomb barrier. (Recoil effects are assumed to be negligible for H and He emission.) The double isotope ratio in Eq. (1) was constructed to cancel out uncertainties due to the unknown isotopic composition of the system which, in equilibrium models, arises from a cancellation of the chemical potential terms. After such a cancellation, the grand canonical distribution provides that [19]

$$R_{H\text{-}He}(E_{K0}) = c\cdot\exp(B/T_{H\text{-}He}) \qquad (2)$$

where c=1.59 is a constant determined by spin values and kinematic factors, B = BE(^{4}He) -BE(^{3}He) -BE(^{2}H) + BE(^{3}H) =14.29 MeV where BE(^{A}X) is the binding energy of isotope ^AX, and $T_{H\text{-}He}$ is the temperature of the system at breakup. (Even for evaporative models, $R_{H\text{-}He}(E_{K0})$ retains a remarkable insensitivity to the isotopic composition of the system [20].) In the limit of thermal equilibrium, $R_{H\text{-}He}(E_{K0})$ should be independent of E_{K0}. On the other hand, for emission from a cooling system, a non-negligible dependence on E_{K0} is predicted.

The solid points in Fig. 2 show the double ratios extracted from the experimental data in Fig. 1 assuming Coulomb barriers for Hydrogen and Helium isotopes of 10 MeV and 20 MeV respectively. The extracted ratios $R_{H\text{-}He}(E_{K0})$ vary from $R_{H\text{-}He}(E_{K0}) \approx 23$, at low values for E_{K0} to $R_{H\text{-}He}(E_{K0}) \approx 10$, at high values of E_{K0}, corresponding to a change in the apparent temperature, $T_{H\text{-}He}$, obtained from Eq. (2), from $T_{H\text{-}He} \approx 3.9$ MeV to $T_{H\text{-}He} \approx 5.2$ MeV. This dependence suggests that the residues formed via central ^{129}Xe+^{nat}Cu collisions undergo an evaporative decay with time for cooling between steps.

To determine the extent to which the observed trend may be reproduced by a time dependent rate equation approach, the decay of residues formed in central $^{129}Xe+^{nat}Cu$ collisions was calculated using the Expanding Evaporating Source (EES) model [5] which assumes evaporative emission of particles from a source that is permitted to expand under its internal pressure. In these calculations, ^{2}H, ^{3}H, ^{3}He and ^{4}He nuclei are emitted from the hot residue or as products from the secondary decay of particle unstable $^{4,5}He$, $^{5,6}Li$ and $^{6,8}Be$ nuclei that are directly emitted from the hot residue. Residues with an initial mass and charge of $A_o = 175$, $Z_o = 77$ and an initial excitation energy of 600 MeV and temperature of about 6.8 MeV were allowed to expand and cool by expansion and particle emission. As discussed in more detail later, the parameters used in the present calculations are slightly different from those in Ref. [11] to provide better agreement with the experimental energy spectra. Calculated energy spectra for ^{2}H (solid lines), ^{3}H (dashed lines), ^{3}He (solid lines) and ^{4}He (dashed lines), are shown in Fig.1 where the agreement is best at energies above the Coulomb barrier. Some discrepancies, visible below the Coulomb barrier may be attributed to the classical barrier penetrabilities in the EES model [5].

The corresponding EES calculations with full time evolutions for the double isotope ratio $R_{H\text{-}He}$(solid lines) are shown in Fig. 2. $R_{H\text{-}He}$ decreases with increasing E_{K0}, consistent with the experimental trends. To demonstrate that the calculated energy dependence of $R_{H\text{-}He}$ originates mainly from the time dependent cooling of the hot residue, the double ratio $R_{H\text{-}He}$ for a single time step at t=70 fm/c corresponding to a single temperature of $T \cong$ 5.2 MeV was calculated. These calculations, shown by the dashed curve in Fig. 2, are only weakly dependent on E_{K0} and inconsistent with the data. The slight dependence on E_{K0} for the single step calculations arises from sequential decays. To assess the effect of sequential feeding, we have performed calculations with single temperature ($T \cong 5.2$ MeV) without sequential feedings from unstable $^{4,5}He$, $^{5,6}Li$ and $^{6,8}Be$ nuclei[21] (dotted curve). The predicted $R_{H\text{-}He}$ from these latter calculations are nearly constant as expected whenever the energy spectra are dominated by a single emission temperature. (For the calculations with full time evolution, the inclusion of secondary decay mainly lowers temperature by about 0.5 MeV over the whole range of E_{K0}.)

The calculations shown in the present work are performed with an initial excitation energy E*= 600 MeV which is larger and an initial collective energy $E_R/A = 0$ which is smaller than the corresponding values E*= 540 MeV and $E_R/A = 0.76$ MeV assumed in ref. [11]. If we use the values of ref. [11] as input parameters in our calculations, the agreement between the measured and calculated energy spectra in Fig. 1 becomes somewhat worse, but Fig. 2 remains essentially unchanged. Thus, it appears that the main signature for cooling is robust with respect to such model dependent uncertainties. This lends confidence to the application of similar techniques to more violent and rapid multifragment disintegrations[22] where the question of whether sufficient time exists for cooling between successive emissions is more strongly contested and where precise values for the excitation energy may be difficult to obtain.

In summary, energy spectra have been measured for Helium and Hydrogen isotopes emitted from highly excited residues produced in central ^{129}Xe+^{nat}Cu collisions at E/A=30 MeV. Differences between the spectra for ^{3}He and ^{4}He nuclei are observed that can be attributed to the time dependent evaporative cooling of the residues. This cooling dynamics can be tested via isotope ratio thermometers; the resulting comparisons indicate a reasonable agreement with present evaporative models. This test provides support for similar studies of more violent and rapid multifragment disintegrations. This work was supported by the National Science Foundation under Grant No. PHY-95-28844 and PHY-93-14131.

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Figure Captions:

Fig. 1: (Upper Panel): Energy spectra, obtained in the c.m. frame for Hydrogen isotopes. and calculated energy spectra for ^{2}H (solid lines) and ^{3}H (dashed lines) using the EES model. (Middle Panel): Energy spectra, obtained in the c.m. frame for Helium isotopes. Calculated energy spectra for ^{3}He (solid lines) and ^{4}He (dashed lines) using the EES model. (Lower Panel): The ^{3}He spectrum (open circles) is normalized to coincide with the ^{4}He spectrum (closed circles) at E_{CM}=20 MeV and the ^{2}H spectra (open squares) is normalized to ^{3}H (closed squares) at E_{CM}=10 MeV.

Fig. 2: The solid points are the double ratios extracted from the experimental data. EES model calculations for the Helium-Hydrogen isotope ratio for the full time evolution of the system (solid line) and for a single temperature of T= 5.2 MeV with sequential decay (dashed line) and without sequential feedings (dotted line).

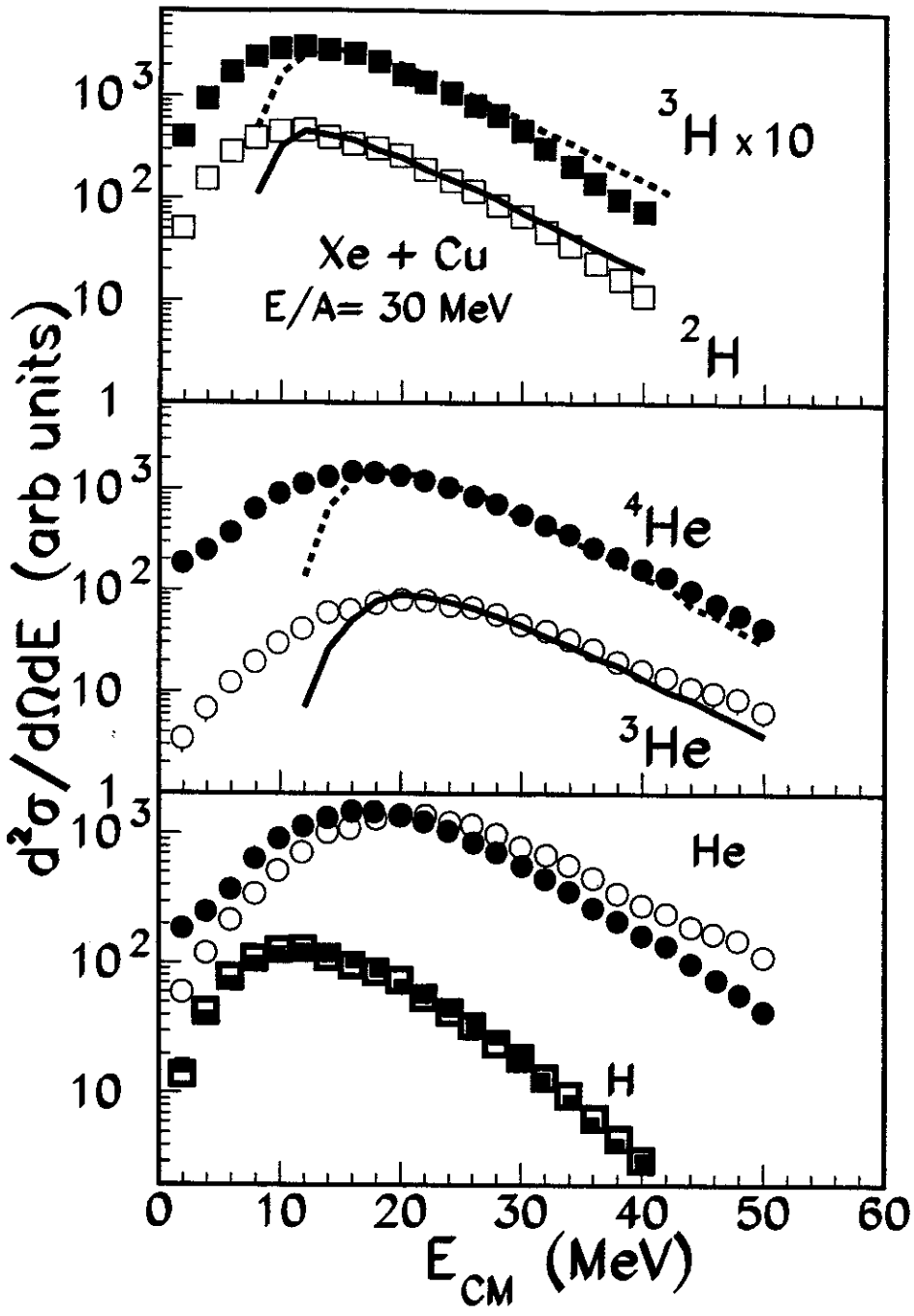
^{3}H x 10
Xe + Cu
E/A= 30 MeV
^{2}H
^{4}He
^{3}He
He
H
$d^2\sigma/d\Omega dE$ (arb units)
E_{CM} (MeV)
0
10
20
30
40
50
60

Fig. 1

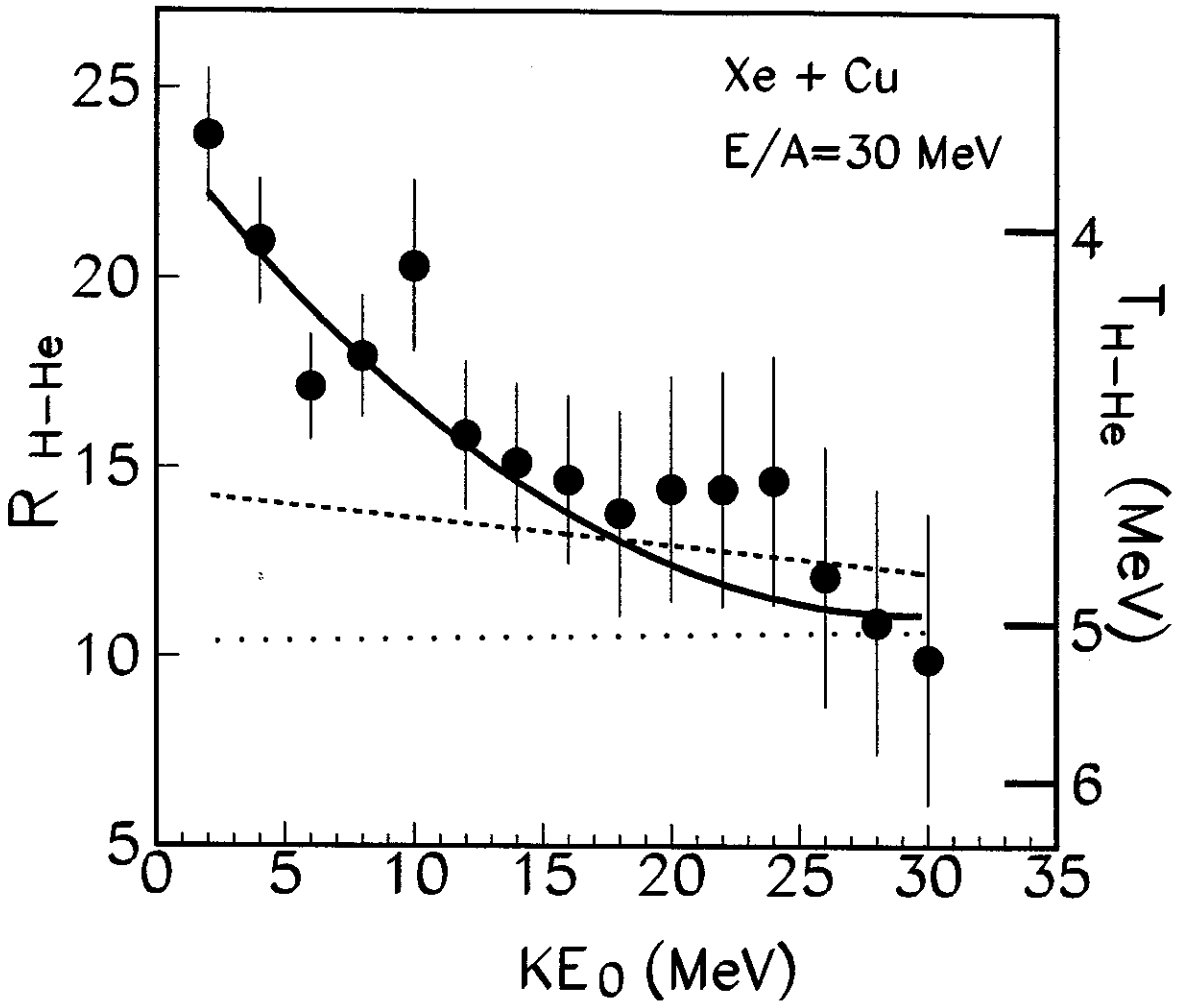
Xe + Cu
E/A=30 MeV
25
20
15
10
5
R_{H-He}
4
5
6
T_{H-He} (MeV)
0
5
10
15
20
25
30
35
KE_0 (MeV)

Fig.2