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Examining the cooling of hot nuclei

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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. [S0556-2813(98)50302-0]

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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 time scale for disintegration. At low-excitation energies, the time scale is long and the system decays sequentially, emitting one particle after another [4–6]. At high-excitation energies, the time scale 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 time scale 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 time scales [8–12]. The observation of a nonnegligible decay time scale, however, does not necessarily imply a cooling between successive emissions and a consequent failure of simultaneous decay models if the decay time scales 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 highly excited nuclei formed in Xe + Cu collisions. Unlike the reactions studied by Refs. [13–16], our system displays neither the mass dependent energy spectra [15–18] nor the problems with statistical interpretations [19,20] that characterize rapidly expanding systems; thus descriptions via evaporative rate equations [4,5] become straightforward.

Previous studies of Xe + Cu collisions at 30*A* 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 for-

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ward angles are dominated by the statistical decay of equilibrated projectilelike 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 [21] calculations. Reproduction of the measured fragment emission velocities and small relative velocity correlations between two intermediate mass fragments (IMF's $3 \leqslant Z \leqslant 9$) 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 after the system has cooled. To test the cooling assumption of the EES model, we have bombarded 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 (MSU). Isotopically resolved light charged particles and IMF's for $Z \leqslant 6$ were detected at $3° \leqslant \theta_{\rm lab} \leqslant 23°$ in the Multics array of 44 gas-Si-CsI telescopes [22]. Light particle energy calibrations accurate to 2% were obtained by irradiating each telescope with ^{228}Th and ^{244}Cm sources and low intensity direct ^{1,2,3}H and ^{3,4,6}He beams. Charged particles were detected at $23° \leqslant \theta_{\rm lab} \leqslant 160°$ by 166 fast plastic-CsI phoswich detectors of the MSU Miniball array [23] and used to assign impact parameters to the collisions, following Ref. [24]. By gating on events with total charged particle multiplicities in the highest 10% of the multiplicity distribution, energy spectra for central collisions were obtained at forward angles $3° \leqslant \theta_{\rm lab} \leqslant 23°$ in this ''reverse kinematics'' Xe + Cu reaction, corresponding to center-of-mass angles less than 70°.

Energy spectra, obtained in the c.m. frame by assuming a center-of-mass velocity of $v_{\rm c.m.}=0.185\ c$ [25], 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 $E_{\rm c.m.}=20$ MeV (open and closed circles). Differences between ^{3}He and ^{4}He spectra have been previously reported for other reactions [13–16]. In contrast, the energy spectra of the hydrogen isotopes have nearly identical shapes, as indicated by the ^{2}H and ^{3}H spectra (open and closed squares) that have been normalized to each other at $E_{\rm c.m.}=10$ MeV.

To examine the cooling trend quantitatively, we explored the double isotope ratio $R_{\rm H-He}(E_{K0})$ [26],

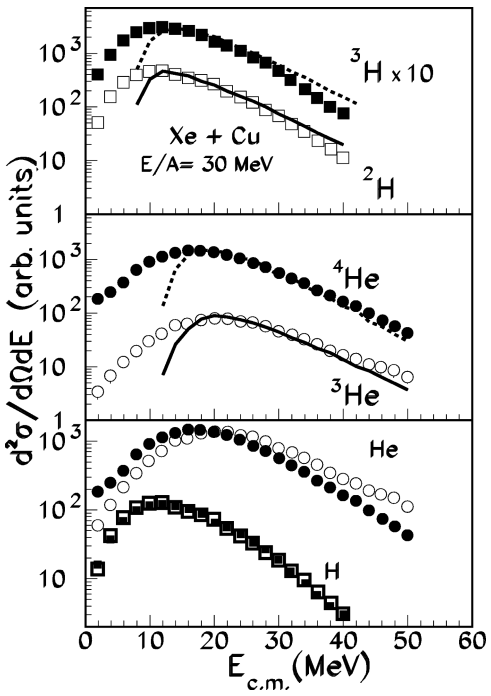

FIG. 1. (Upper Panel): Energy spectra, obtained in the c.m. frame for hydrogen isotopes and calculated energy spectra for ^{2}H (solid lines) and ^{3}H (dashed lines) using the EES model. (Middle Panel): Energy spectra, obtained in the c.m. frame for helium isotopes. Calculated energy spectra for ^{3}He (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 $E_{\rm c.m.}=20$ MeV and the ^{2}H spectra (open squares) is normalized to ^{3}H (closed squares) at $E_{\rm c.m.}=10$ MeV.

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

where $Y(A^X, E_{K0})$ is the yield for isotope A^X, $E_{K0}=E_{{\rm c.m.},i}-V_i$ is the kinetic energy, neglecting recoil, of the emitted particle in the c.m. system prior to Coulomb acceleration, $E_{{\rm c.m.},i}$ is the observed c.m. kinetic energy, and V_i is the Coulomb barrier. The double isotope ratio in Eq. (1) removes the sensitivity to the isotopic composition of the system [26,27]. After such a cancellation, the grand canonical distribution provides that [26]

$$R_{\rm H-He}(E_{K0}) = c\ \exp(B/T_{\rm H-He}), \quad (2)$$

where $c=1.59$ is a constant determined by spin values and kinematics factors, $B=E_b(^4{\rm He}) - E_b(^3{\rm He}) + E_b(^2{\rm H}) - E_b(^3{\rm H})=14.29$ MeV where $E_b(^A{\rm X})$ is the binding energy of isotope A^X, and $T_{\rm H-He}$ is the temperature of the system at breakup. In the static limit of thermal equilibrium, $R_{\rm H-He}(E_{K0})$ and $T_{\rm H-He}$ should be independent of E_{K0}. For emission from a cooling system, on the other hand, one may expect $T_{\rm H-He}$ to increase with E_{K0}.

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 $R_{\rm H-He}(E_{K0})$ vary from $R_{\rm H-He}(E_{K0}) \approx 23$, at low values for E_{K0} to $R_{\rm H-He}$

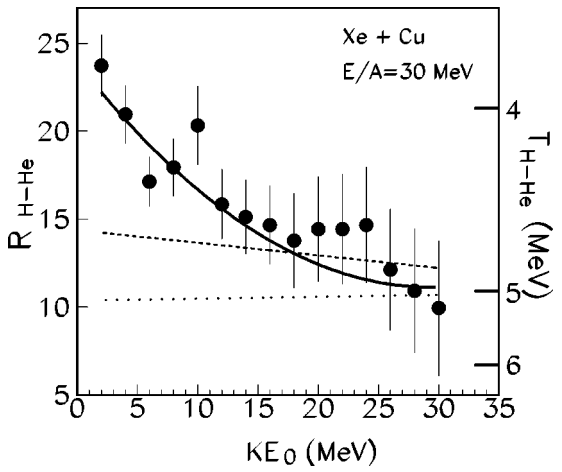

FIG. 2. The solid points are the double ratios extracted from the experimental data. EES model calculations for the helium-hydrogen isotope ratio for the full time evolution of the system (solid line) and for a single temperature of $T=5.2$ MeV with (dashed line) and without (dotted line) sequential feeding.

$(E_{K0})\approx 10$, at high values of E_{K0}, corresponding to a change in the apparent temperature, $T_{\mathrm{H-He}}$, obtained from Eq. (2), from $T_{\mathrm{H-He}}\approx$ 3.9 MeV to $T_{\mathrm{H-He}}\approx$ 5.2 MeV. This dependence suggests that the nuclear systems formed via central ^{129}Xe + $^{\mathrm{nat}}$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 + $^{\mathrm{nat}}$Cu collisions was calculated using the 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 [28]. Residues with an initial mass and charge of $A_0=175$, $Z_0=77$ 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 of the present calculations differ slightly from those in Ref. [11] and provide a 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), shown in Fig. 1, agree best with the data at energies above the Coulomb barrier. Discrepancies below the Coulomb barrier can be expected due to the classical barrier penetrabilities in the EES model [5].

The corresponding EES calculations for the double isotope ratio $R_{\mathrm{H-He}}$(solid lines) are shown in Fig. 2. $R_{\mathrm{H-He}}$ decreases with increasing E_{K0}, consistent with the experimental trends. To demonstrate that the calculated energy dependence of $R_{\mathrm{H-He}}$ originates mainly from the time dependent cooling of the hot residue, the double ratio $R_{\mathrm{H-He}}$ for a single time step at $t=70$ fm/c corresponding to a single temperature of $T\approx 5.2$ MeV was calculated. These calculations, shown by the dashed curve in Fig. 2, depend only weakly on E_{K0}, in contrast to the data. To demonstrate that this weak energy dependence arises from the secondary decay of heavier particle unstable nuclei, we have performed calculations, also with a single temperature ($T\approx 5.2$ MeV), but neglecting the feeding from the sequential decay of unstable ^{4,5}He, ^{5,6}Li, and ^{6,8}Be nuclei (dotted curve). These latter calculations predict a nearly constant $R_{\mathrm{H-He}}$, as expected whenever the energy spectra are dominated by a single emission temperature. [In the calculations with the full time evolution (solid line), the inclusion of secondary decay lowers $T_{\mathrm{H-He}}$ by about 0.5 MeV, roughly independent 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 the ratios in Fig. 2 remain nearly the same. (Variations in E^*, E_R/A, or A of the order of 10–15% results in variations of less than 5% in the apparent temperature.) Thus, the main signature for cooling is robust with respect to such model dependent uncertainties. It is noteworthy that the EES model predicts roughly 30% of the hydrogen and helium emission to occur within 100 fm/c; thus cooling may occur before all the degrees of freedom or decay modes of the hot residue are fully thermalized. Thus, it is likely that similar cooling processes are important for more violent and rapid multifragment disintegrations where it is often assumed that insufficient time exists for cooling between successive emissions. The identification of cooling phenomena in more explosive collisions [16] merits a high priority.

In summary, energy spectra have been measured for helium and hydrogen isotopes emitted from highly excited residues produced in central ^{129}Xe + $^{\mathrm{nat}}$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.

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[1] J. Randrup and S. E. Koonin, Nucl. Phys. **A356**, 223 (1981).
[2] D. H. E. Gross, Phys. Rep. **279**, 119 (1997).
[3] J. Bondorf *et al.*, Nucl. Phys. **A433**, 321 (1985).
[4] W. A. Friedman and W. G. Lynch, Phys. Rev. C **28**, 16 (1983).
[5] W. A. Friedman, Phys. Rev. C **42**, 667 (1990).
[6] W. Hauser and H. Feshbach, Phys. Rev. **87**, 366 (1952).
[7] W. G. Lynch, Annu. Rev. Nucl. Part. Sci. **37**, 493 (1987), and references therein.
[8] D. H. Boal *et al.*, Rev. Mod. Phys. **62**, 553 (1990).
[9] D. R. Bowman *et al.*, Phys. Rev. Lett. **70**, 3534 (1993).

[10] E. Bauge *et al.*, Phys. Rev. Lett. **70**, 3705 (1993).
[11] D. R. Bowman *et al.*, Phys. Rev. C **52**, 818 (1995).
[12] D. Durand *et al.*, Phys. Lett. B **345**, 397 (1995).
[13] K. G. R. Doss *et al.*, Mod. Phys. Lett. A **3**, 849 (1988).
[14] G. Poggi *et al.*, Nucl. Phys. **A586**, 755 (1995).
[15] M. A. Lisa *et al.*, Phys. Rev. Lett. **75**, 2662 (1995).
[16] R. Bougault *et al.*, LPCC 97-04.
[17] S. C. Jeong *et al.*, Phys. Rev. Lett. **72**, 3468 (1994).
[18] W. C. Hsi *et al.*, Phys. Rev. Lett. **73**, 3367 (1994).
[19] W. Reisdorf *et al.*, Nucl. Phys. **A612**, 493 (1997).
[20] C. Williams *et al.*, Phys. Rev. C **55**, R2132 (1997).
[21] M. Colonna *et al.*, Prog. Part. Nucl. Phys. **30**, 17 (1993).
[22] I. Iori *et al.*, Nucl. Instrum. Methods Phys. Res. A **325**, 458 (1993); M. Bruno *et al.*, *ibid.* **311**, 189 (1992); N. Colonna *et al.*, *ibid.* **321**, 529 (1992); P. F. Mastinu *et al.*, *ibid.* **338**, 419 (1994).
[23] R. T. de Souza *et al.*, Nucl. Instrum. Methods Phys. Res. A **295**, 109 (1990).
[24] M. J. Huang *et al.*, Phys. Rev. Lett. **78**, 1648 (1997).
[25] This value is slightly larger than the value $v_{\mathrm{source}}=0.175\ c$ obtained in Ref. [11] for events with two observed fragments. The double ratio analysis is not very sensitive to the source velocity; changing the source velocity by 5% alters $T_{\mathrm{H-He}}$ by about 50 KeV.
[26] S. Albergo *et al.*, Nuovo Cimento A **89**, 1 (1985).
[27] G. Kunde *et al.*, Phys. Lett. B (in press).
[28] The influence of secondary decay on the spectra has been qualitatively described by M. A. Bernstein *et al.*, Phys. Rev. C **29**, 132 (1984). Contributions due to the decays of even heavier fragments have been estimated via the feeding calculations of Nayak *et al.*, *ibid.* **45**, 132 (1992), and have been found to be small (i.e., of the order of 5%).