EXAMINING THE COOLING OF HOT NUCLEI

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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, 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. Isotopically resolved light charged particles and IMF's for Z<6 were detected at 3 ^{o} <theta_lab <23 ^{o} in the Multics array of 44 gas-Si-CsI telescopes [1]. Charged particles were detected at 23 ^{o} <theta_lab<160 ^{o} by 166 fast plastic-CsI phoswich detectors of the MSU Miniball array [2] and used to assign impact parameters to the collisions. 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^o<theta_lab<23^o in this ``reverse kinematics'' Xe + Cu reaction, corresponding to center of mass angles less than 70 degree.

Energy spectra, obtained in the c.m. frame by assuming a center of mass velocity of v_{cm}= 0.185 c, 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). Differences between ^{3}He and ^{4}He spectra have been previously reported for other reactions [3-6].

To examine the cooling trend quantitatively, we explored the double isotope ratio $R_{HHe}(E_{K0})$ [7].

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

where $Y(^AX, E_{K0})$ is the yield for isotope ^AX, E_{K0}= Ecm,i - V_i is the kinetic energy, neglecting recoil, of the emitted particle in the c.m. system prior to Coulomb acceleration, Ecm,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 [7, 8]. After such a cancellation, the grand canonical distribution provides that [7]

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

where c=1.59 is a constant determined by spin values and kinematics 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 ^{A}X, and $T_{H\text{-}He}$ is the temperature of the system at breakup. In the static limit of thermal equilibrium, $R_{H\ He}(E_{K0})$ and $T_{H\text{-}He}$ should be independent of E_{K0}. For emission from a cooling system, on the other hand, one may expect $T_{H\text{-}He}$ 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 $R_{H\text{-}He}$ (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 nuclear systems formed via central ^{129}Xe + ^{nat}Cu collisions undergo an evaporative decay with time for cooling between steps.

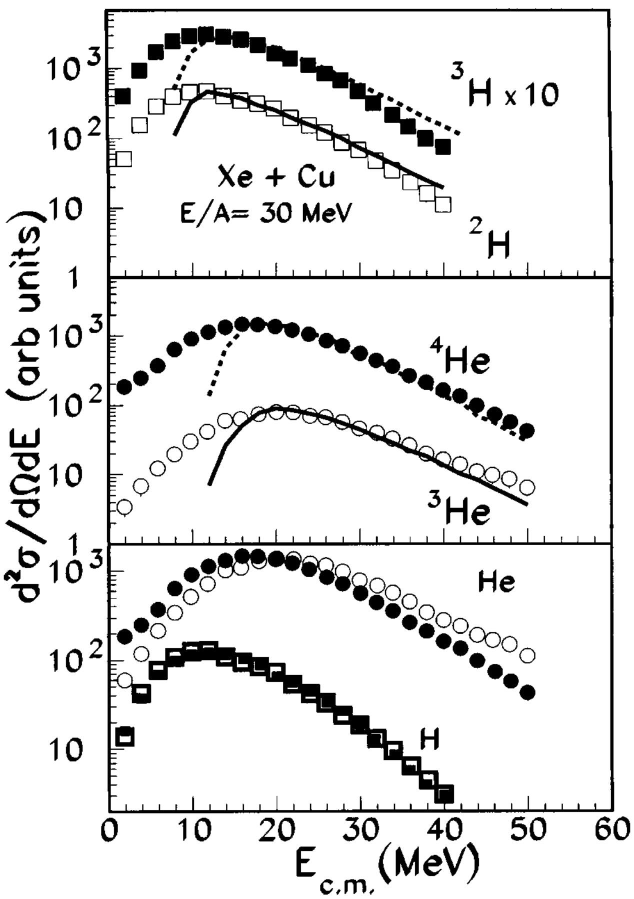

Fig. 1: (Upper Panel): Energy spectra, obtained in the c.m. frame for Hydrogen isotopes. and calculated energy spectra for ^{2}H (solid lines) and ^{3}H (dashed lines) using the EES model. (Middle Panel): Energy spectra, obtained in the c.m. frame for Helium isotopes. Calculated energy spectra for ^{3}He (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.

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 [9] which assumes evaporative emission of particles from a source that is permitted to expand under its internal pressure. 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. The parameters of the present calculations differ slightly from those in Ref. [10] 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 ^4He (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 penetrability in the EES model [9].

The corresponding EES calculations 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 ~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~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 $R_{H\text{-}He}$, 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 $T_{H\text{-}He}$ by about 0.5 MeV, roughly independent of E_{K0}.

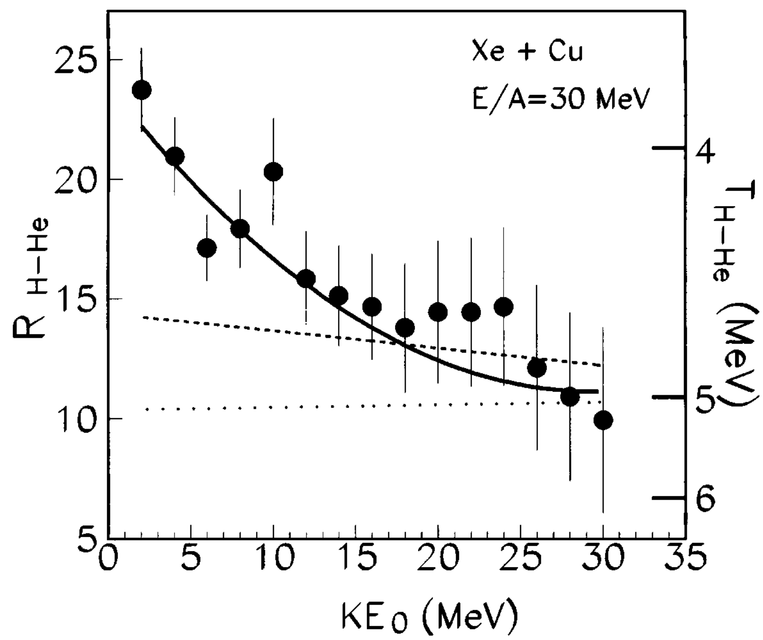

Fig. 2: The solid points are the double ratios extracted from the experimental data. EES model calculations for the Helium-Hydrogen isotope ratio for the full time evolution of the system (solid line) and for a single temperature of T= 5.2 MeV with (dashed line) and without (dotted line) sequential feeding.

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 ^3He and ^4He 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.

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