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Limiting temperatures of neutron rich nuclei: A possible interpretation of data from isotope yield ratios

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The recent ALADIN report of limiting temperatures for nuclear disassembly, derived from measurements of isotopic ratios for He and Li nuclei, is discussed. It is suggested that the entire excitation energy dependence which is observed may result from the fact that limiting temperatures for the onset of Coulomb instability are being measured for progressively lighter neutron rich nuclei as the excitation energy per nucleon increases. While the basic observation of plateauing in the intermediate excitation energy range remains valid, the higher excitation results may not signal entry into the vapor phase. The ALADIN result for $A\approx 125$, when combined with lower energy data, indicates a plateau temperature near 6.5 MeV over the range of 3–11 MeV/nucleon initial excitation energy.

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I. INTRODUCTION

Since the pioneering work of Bonche *et al.* on the calculations of the limiting temperature $T_{\rm lim}$, at which a nucleus enters into the region of Coulomb instability [1–3], a number of other authors have addressed this problem using various theoretical approaches involving both static and dynamic calculations [4–10]. The calculations are in general sensitive to the assumed formulations of the nuclear equation of state and the surface energy. They typically lead to limiting temperatures which decrease with increasing mass. In the intermediate mass region they are in the neighborhood of 5 to 7 MeV. Experimental attempts to determine limiting temperatures have been made using measured spectral slopes [11–13], state ratios [14–16], and isotope ratios [17,18]. For medium mass nuclei such measurements indicate a plateauing of the temperature at excitation energies above $\approx$3 MeV/u [11,15,18]. Interpretation of the results obtained using each of these techniques involves some assumptions on the de-excitation mechanism and some model corrections [19]. These measurements give quite strong evidence for limiting temperatures whose magnitudes and mass dependence are in reasonable accord with theoretical predictions. Such limiting temperatures appear to be associated with a cluster phase change in nuclei.

II. THE ALADIN LIMITING TEMPERATURES

Recently the ALADIN group, using a technique which appears ideally suited to study thermally driven phase transitions, has provided a stimulating and self-consistent set of limiting temperature data over the widest range of excitation energy per nucleon yet sampled in limiting temperature determinations [18]. These temperatures, obtained from measurements of the isotope yield ratios ^{3}He/^{4}He and ^{6}Li/^{7}Li [17], are designated $T_{\rm HeLi}$ and presented as a function of excitation energy per nucleon in Fig. 2 of their paper. The authors note that model calculations using the sequential evaporation code GEMINI [20], the microcanonical multifragmentation code of Gross [8], and the quantum statistical model [21], at densities greater than $0.5\rho_0$, all suggest a near linear relationship between $T_{\rm HeLi}$ and the initial temperature T of the de-exciting system, as well as a "rather constant ratio of 0.85 ± 0.5 between $T_{\rm HeLi}$ and the thermodynamic temperature of the system."

A linear dependence of $T_{\rm apparent}$ vs $T_{\rm initial}$ has previously been derived from empirical data for slope temperature measurements of ^{4}He evaporated from nuclei with $A\approx 125$, and it has been suggested that the state ratio temperatures for ^{4}He and ^{5}Li should exhibit a very similar behavior [22]. For the measured ^{4}He slope temperatures, which are in the range of $T_{\rm apparent}=3.5$–6 MeV, the empirical ratio of $T_{\rm apparent}/T_{\rm initial}$ is observed to be 0.84 [22]. This factor is in excellent agreement with that which has been derived from the model estimates for $T_{\rm HeLi}$, a comforting result since He isotopes are involved in both techniques.

In Fig. 1 of this paper, we present the results of the ALADIN experiment [18]. Here the $T_{\rm HeLi}$ temperatures are plotted against $\langle E_0\rangle/\langle A_0\rangle$ where $\langle E_0\rangle$ is the average initial excitation energy of the decaying system and $\langle A_0\rangle$ is the average mass number of that system. Both $\langle E_0\rangle$ and $\langle A_0\rangle$ are reconstructed from the experimental data. Only the data for 600 MeV/u ^{197}Au + ^{197}Au are shown. The data presented in Fig. 2 of Ref. [18] include some $T_{\rm HeLi}$ information from more asymmetric collisions at lower energies. These show a steady rise in temperature to excitation energies $\approx$3 MeV/nucleon. This rise, typical of fermionic systems, is approximated in Ref. [18] by $T=\sqrt{K\langle E_0\rangle/\langle A_0\rangle}$ with $K=10$. More detailed experiments have revealed that the inverse level density parameter K actually decreases as the energy decreases in this excitation energy range [23,24]. The initial temperature rise is followed by an extended plateau region where $T_{\rm HeLi}$ increases slowly from $\approx$4.6 to 5.5 MeV over the excitation energy range of 2–10 MeV/nucleon and then a sharp increase in temperature to 9 MeV as the excitation energy increases to 15 MeV/nucleon. This latter increase is particularly striking and it has been suggested that this may signal the transition from the clusterization region into the vaporization regime. The authors note however that more complete calculations using an internally consistent equation

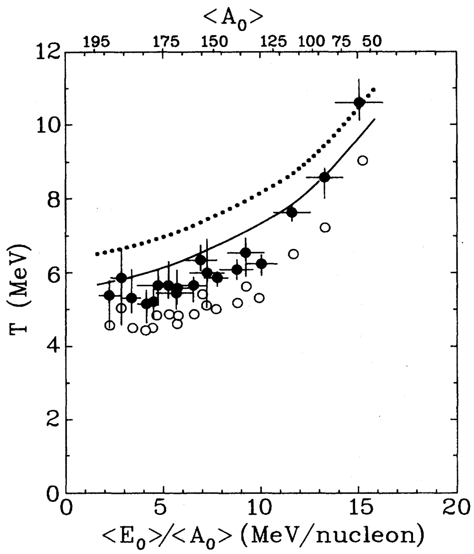

FIG. 1. Limiting temperature measurements from the ALADIN experiment. The mass scale at the top indicates masses sampled by the data. The open symbols represent the T_{HeLi} temperature measurements. The solid symbols represent $T_{\mathrm{initial}} = T_{\mathrm{HeLi}}/0.85$. The dotted line indicates the calculated limiting temperatures from Ref. [6]. The solid line is obtained by subtracting 0.8 MeV from the values from Ref. [6] (see text).

of state are necessary before more definite conclusions can be drawn.

III. A POSSIBLE INTERPRETATION

While it is possible that the transition into the vapor regime has been observed, it should be noted that the ALADIN data are not for a single well-defined nucleus, but for a series of nuclei whose mass numbers A_0 range from 195, near that of the projectile, down to 53, as can be seen in the first figure of Ref. [18]. Further, as is also obvious from that figure, the excitation energy per nucleon is completely correlated with the mass so that the lightest mass nuclei have the highest excitation energies. This strong mass variation should be considered in interpreting these data.

At the top of Fig. 1 we have added a mass scale indicating the mass variation which is associated with the excitation energy per nucleon scale at the bottom. This mass scale is derived from the two parts of Fig. 1 of Ref. [18].

To compare the observed trends with theoretical expectations, we use the results of two limiting temperature calculations which appear in the literature. The first, that of Besprovany and Levit [6] is an extension of the original Levit and Bonche [3] work and includes calculations over the full range of N and Z for which protons and neutrons are bound. Their results are presented in Fig. 2. The second by Song and Su [7] is also of interest because, although restricted to nuclei along the line of beta stability, it includes a set of calculations employing the same surface energy ansatz [25] as Besprovany and Levit, but a number of different Skyrme interactions. This work shows that while the absolute values of T_{lim} depend on the interaction chosen, a decrease of T_{lim} with increasing mass is always predicted. It shows also that

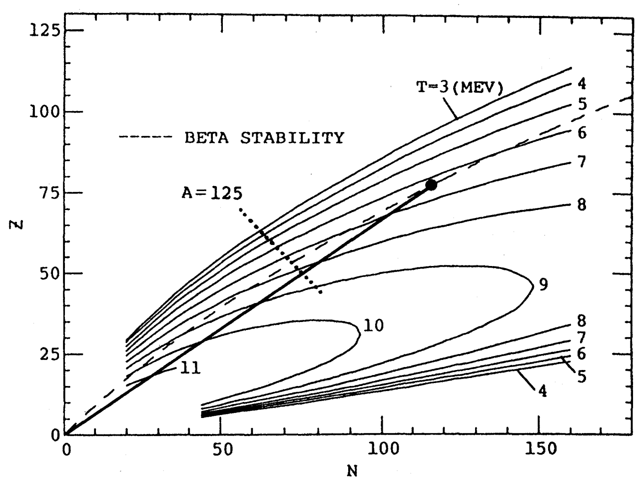

FIG. 2. Limiting temperature as a function of neutron and proton number (Ref. [6]). The solid line indicates the locus of projectile fragments with $N/Z = 1.49$. The short dashed line is the line of beta stability.

there is a direct correspondence between T_{lim} and T_c, the critical temperature for nuclear matter, with which the assumed surface dependence is characteristic of a particular Skyrme interaction. Results of the Song and Su calculation are presented in Fig. 3.

To explore the extent to which the two calculations cited might explain the ALADIN data, we proceed as follows:

(1) We first correct the T_{HeLi} temperatures of Ref. [18] to initial temperatures by dividing the T_{HeLi} temperatures (and their errors) by 0.85 as suggested by the model calculations. This seems to be a reasonable initial step since this value is derived from several models and only the quantum statistical model, applied at quite low densities, leads to a significantly different ratio. While some thermal expansion may occur in these systems, it is unlikely to be large over much of the lower excitation energy range covered by these data. The resultant trend of T_{initial} is represented by the solid circles in Fig. 1.

(2) Using the results of the Besprovany and Levit calcu-

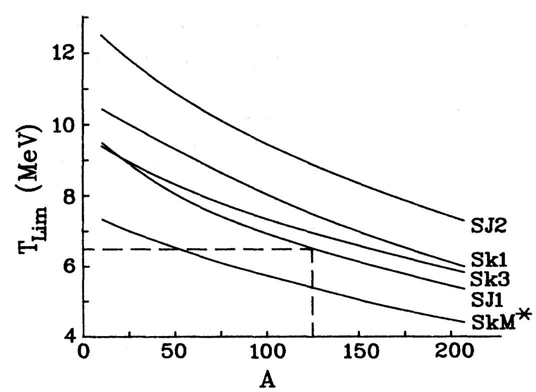

FIG. 3. Limiting temperatures calculated using various Skyrme interactions (Ref. [7]). The experimental result for $A \approx 125$ (Ref. [11]) is indicated by the dashed line.

lation, we have extracted limiting temperatures for the excited projectile remnants of a given $\langle A_0 \rangle$ assuming that the N/Z ratio of the remnant is the same as that of the ^{197}Au projectile. It is possible that some isospin fractionation may occur which shifts this slightly, but the experimental data do not contain sufficient information to determine Z_0 and N_0. The heavy straight line in Fig. 2, terminating at $Z=79$, $N=118$ indicates the locus along which such neutron rich nuclei would be found. The extracted variation of these calculated limiting temperatures over the mass range sampled on the experiment is presented as a dotted line in Fig. 1. While the quantitative agreement between this curve and that for T_{initial} derived from the data is poor, the general trend seen in the two lines is quite similar.

(3) Our own limiting temperature measurements for nuclei with $A \approx 125$ at excitation energy near 4 MeV/nucleon lead to a value of T_{lim} near 6.5 ± 0.5 MeV [11], close to the value obtained for this mass region at higher excitation energy in the ALADIN experiment, using the procedures described above. Our system is, however, slightly neutron deficient. A comparison between our results and those of the Song and Su calculations has shown that their calculations, employing Skyrme interactions such as SJ1 ($K_\infty=222$ MeV) which corresponds to a critical temperature T_c near 17 MeV, are in best agreement with our data [26] (Fig. 3). Although Song and Su have not provided results for neutron rich nuclei, a comparison of the Song and Su calculations using SJ1 with the Besprovany and Levit calculation which was based on results with a SK1 interaction can be made for beta stable nuclei. This comparison indicates that the limiting temperatures calculated by Song and Su are systematically ≈ 0.8 MeV lower than those calculated by Besprovany and Levit. To proceed, we assume that this difference is that which would result if the Song and Su calculations were extended to neutron deficient nuclei. Therefore, in Fig. 1, we present, as a solid line, the temperatures obtained by subtracting 0.8 MeV from those of the Besprovany and Levit calculations. This procedure is obviously oversimplified and more extended calculations using the Song and Su formalism are certainly desirable. At the same time we note that the resultant curve, thus calibrated to our measurement for $A \approx 125$, is in rather striking agreement with the ALADIN data, particularly when the experimental uncertainties and possible variations in the N/Z ratio of the primary fragment are considered. This is the basis for our suggestion that the higher excitation energy data may not reflect entry into the vaporization phase.

IV. SUMMARY AND CONCLUSION

An interpretation of the ALADIN limiting temperature results, which takes into account the strong correlation between the primary fragment mass and the excitation energy deposition suggests that the higher excitation energy data may not sample the vaporization regime. The ALADIN group has already noted that the T_{HeLi} technique demands that in the very highest excitation energy range studied $\approx 20\%$ of the mass of the decaying system is still in intermediate mass fragments.

Even if the vaporization regime has not been sampled, the ALADIN data do provide a much more extensive and self-consistent set of limiting temperature data than have previously been available and thus represent an important advance in our efforts to determine the nuclear equation of state and critical temperature for nuclear matter. The N/Z dependence of the calculations, though significant, does not destroy the basic feature of the extended plateau in the intermediate excitation energy region.

In this regard, it is interesting to note that the ALADIN data appear to sample nuclei with $A \approx 125$ at ≈ 11 MeV/nucleon excitation energy. This is the mass range which we have sampled to 4.4 MeV/nucleon but for more neutron deficient isobars. The T_{HeLi} from the ALADIN data at $A \approx 125$ is ≈ 6.1 MeV, which indicates $T_{\text{initial}} \approx 7.2$ MeV. From the Besprovany and Levit calculations [6] we estimate that these neutron rich nuclei should exhibit limiting temperatures about 1.1 MeV higher than the slightly neutron deficient nuclei sampled in Ref. [11]. Subtracting this 1.1 MeV from the ALADIN results, we would find a temperature T_{initial} of 6.1 MeV at 11 MeV/nucleon in reasonable agreement with the 6.5 MeV $\pm$ 0.5 MeV determined in our measurements at 4 MeV nucleon. Together the data define the caloric curve from $A \approx 125$ over a wide range of energy and suggest a plateau temperature near 6.5 MeV at excitation energies from 4 to 11 MeV/nucleon. This trend is quite similar to that calculated by Gross for $A=131$ although the absolute values are slightly higher than those calculated [8,11]. It is clear that better characterization of N and Z in the primary fragments, coupled with model calculations which span the appropriate range of isospin would be of great value. Refined investigations on the range of applicability of the HeLi temperature measurement and its interpretation are also called for.

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