Decay of Very Hot Nuclei

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The decay channels of $^{238}U^*$ excited to energies between 10 and 1800 MeV are sampled by a microcanonical Monte Carlo calculation; i.e., the total energy, momentum, baryon number, and charge are strictly conserved quantities. From samples of about 2×10^6 complete events, various averages are calculated, such as the number N_c of charged fragments, the number of prompt and of evaporated neutrons, the temperature, and the multiplicity of heavy fragments. The distributions of the multiplicity N_c and of the temperature T are calculated as well.

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The statistical decay of nuclei at low excitation energies by evaporation of neutrons or α particles is well described by the Weisskopf model. Nothing, however, is known about the decay modes at higher excitations (up to $E^*\sim2$ GeV). Recent experiments[1] try to explore the limits for the excitation energy which a nucleus is able to accept. To answer this question it is essential to know how a highly heated nucleus decays. In this paper we show that $^{238}U^*$ ($E^*\gtrsim1$ GeV) decays predominantly into three or more heavy fragments ($A\geq20$). Thus the disappearance of binary fission events found at $E^*\gtrsim1$ GeV[1] appears in a new light. One cannot conclude that such very hot nuclei do not exist.

In analogy to the Weisskopf model the *statistical* decay of a nucleus is *defined* by the following hypothesis:

(i) During the expansion of the system a freezeout configuration exists where the rearrangement of the fragments by the exchange of nucleons ceases. Here we assume that this is the case when the average distance between the fragments is ~2 fm, i.e., where the fragments occupy a sphere with the radius $R=2.08A_t^{1/3}$.

(ii) All decay channels out of this configuration with the prescribed total energy E_t, momentum $\mathbf{P}_t=0$, baryon number A_t, and charge Z_t are equally probable. That is, we assume that the quantal decay probability $P_{if}=|T_{if}|^2\rho_f$ is dominated by the phase-space factor ρ_f, the product of the δ functions for the four fundamental, global conservation laws $(E_t,\mathbf{P}_t,A_t,Z_t)$.

It should be noticed that this definition is free of any assumption about long equilibration times. It is consistent with the fundamental assumption of equal *a priori* probabilities for the accessible states, which is the starting point of statistical mechanics (cf. Fowler and Guggenheim or Tolman[2]). *Only by comparing the predictions of the statistical model with the experimental data can one draw a conclusion about the existence of any direct mechanism*, which leads to a strong variation of the transition matrix $|T_{if}|^2$.

In contrast to other "statistical" treatments of nuclear multifragmentation,[3-5] or to the liquid-gas phase-transition model,[6] we take the four fundamental conservation laws strictly into account. It must be pointed out that finite nuclei behave differently from nuclear matter: The Coulomb interaction has a range much longer than the dimensions of the system. This leads to a *quadratic* dependence of the energy on the mass partition, and invalidates many familiar thermodynamic relations [e.g., the free energy $F(p,T)$ or the entropy S of the system is no longer the sum of the free energy or entropy of its constituents as assumed by Siemens[6] and Bondorf *et al.*[7]]. The *strong* and *nonlinear* variation of the binding energy and the Coulomb interaction between the fragments by hundreds of megaelectronvolts is the crucial constraint to the selection and the statistical weight of the decay channels. A linear approximation of the Coulomb interaction as in Ref. 6 is insufficient; also the Wigner-Seitz approximation used in Ref. 7 misses the variation of the total Coulomb energy by a significant amount (measured in units of the temperature).

A strict *microcanonical* sampling of an interacting many-body system is new and especially a microcanonical treatment of *nuclear* decay. Usually a canonical calculation is performed or in some cases[8] a pseudo-microcanonical one. Therefore our calculation is interesting from a more general point of view also. It allows for the comparison of canonical and microcanonical averages and distributions. In this Letter we will not describe technical details. These will be published separately later.[9] In the following, we describe some of the results which we believe are important for nuclear physics.

Before we do so, we list the basic ingredients and simplifications (cf. also Ban-hao and Gross[10] and Gross and Zhang[11,12]). Here, and in contrast to Refs. 10–12, the binding energies are the experimental ones where available, or include shell, pairing, and deformation effects.[13,14] The internal level densities are the experimental ones for $A\leq40$ and/or are taken from Truran, Cameron, and Hilf[13] including pairing and shell corrections up to the lowest particle decay barriers. Neutron evaporation is calculated by our assum-

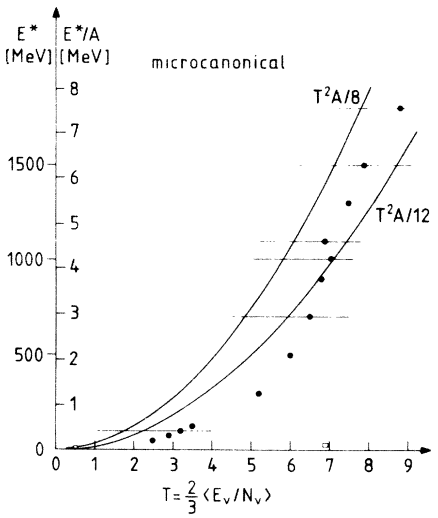

FIG. 1. Excitation energy E^* vs temperature $T=\frac{2}{3}\langle E_\nu/N_\nu\rangle$. The bars represent the FWHM of the temperature *distributions.*

ing the neutrons to be distributed according to a Fermi gas inside a potential 50 MeV deep and with a radius of $1.224A^{1/3}$. The evaporation of α's above the decay barrier is assumed to be prompt; i.e., only long-living *neutron* resonances are assumed to be excited above the lowest decay barrier in the nascent fragments. This might be a serious reduction of the internal phase space. However, we do not see any possibility to be more rigorous on this point. In general, the results of the model are relatively insensitive to the details of the internal phase space. Angular momentum is allowed to fluctuate but to be zero on the average. The temperature T is taken to be $\frac{2}{3}$ times the average total energy of prompt neutrons per prompt neutron. Fragments are not allowed to be dynamically deformed. All fragments sampled are secondary fragments *after* neutron evaporation.

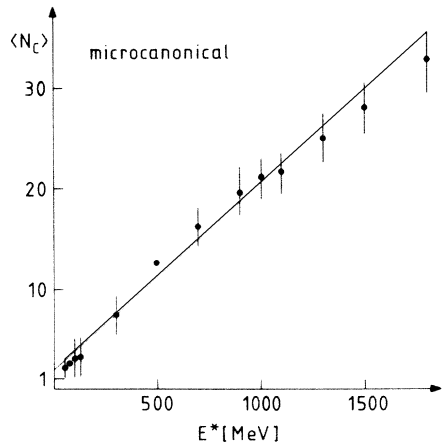

FIG. 2. Multiplicity $\langle N_c\rangle$ of charged fragments vs excitation energy E^*. The bars give the FWHM of the N_c *distributions.*

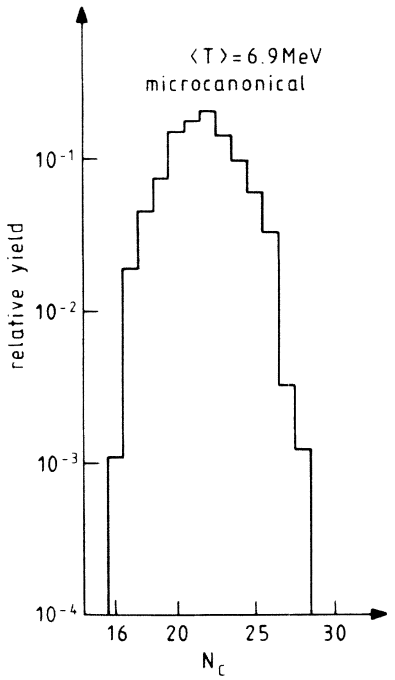

FIG. 3. Distribution of N_c at $E^*=1101$ MeV.

Figure 1 shows the mean temperature $\langle T\rangle$ as a

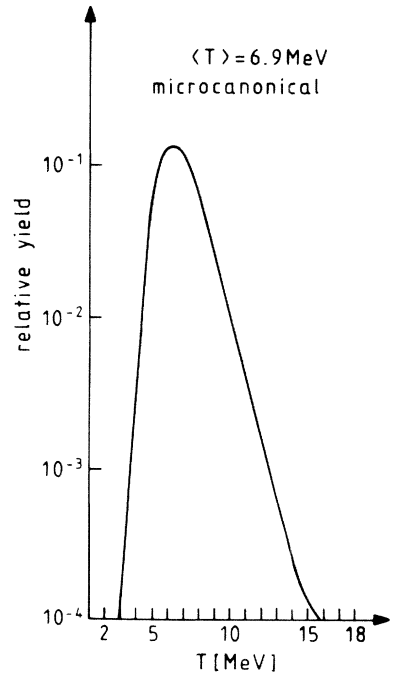

FIG. 4. Distribution of the temperature T at $E^*=1101$ MeV.

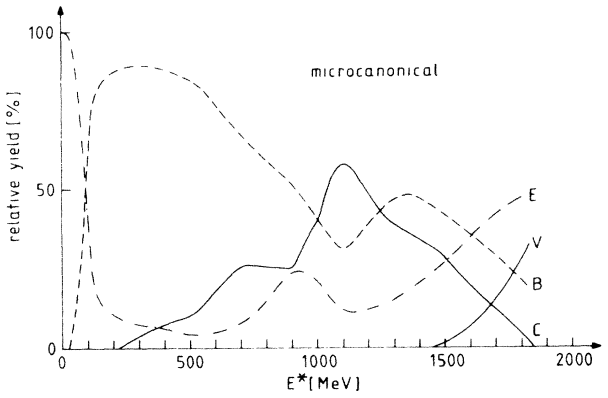

FIG. 5. Relative yield (in percent) of the four decay types (see text) vs excitation energy E^*.

function of the excitation energy E^*. $E^*(T)$ follows roughly $T^2A/12$. At extremely small E^*, strong fluctuations of $T=\frac{2}{3}\langle E_\nu/N_\nu\rangle$, especially near decay thresholds, show up. The bars give the FWHM of the temperature distributions.

Figure 2 shows the mean multiplicity $\langle N_c\rangle$ of prompt charged fragments for various excitation energies E^*. The bars again represent the FWHM of the N_c distributions. $\langle N_c\rangle$ follows nicely a straight line, $\langle N_c\rangle \approx 2+E^*/(54\text{ MeV})$. That is, for every 54 MeV more excitation one more charged fragment (and one more neutron) is produced on the average. Most of this energy goes into the new surface and only very little goes into heat. The distribution of N_c is shown for a typical case in Fig. 3. The N_c distributions are smooth and Gaussian shaped which proves the statistical significance of our results. Figure 4 gives the temperature distribution. Again, this is very smooth and is Maxwellian-like.

In order to gain insight into the characteristic details of the decay properties, more exclusive information is needed. Figure 5 classifies the decay channels into four groups: E (pseudoevaporation)—only one fragment has $A \geq 20$; B (pseudofission)—only two fragments have $A \geq 20$; C (cracking)—three or more fragments have $A \geq 20$; and finally V (vaporization)—all fragments have $A < 20$. Evidently for E^* around 1000 MeV the cracking mode becomes the dominant one. This *might* be an explanation for the disappearance of fissionlike two-fragment correlations found in the experiments.[1] The significance of the cracking mode for the energy spectrum was discussed in Ref. 11.

We also calculated the time that the system needs to increase the average distance between the fragments by 2 fm, which is about the range of nuclear forces. This *decay time* turns out to be about 2×10^{-21} sec for the whole range of excitation energies. It is thus much longer than conventionally assumed.

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