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Temperatures, energies, and degree of thermal equilibration of fragments in damped nuclear reactions

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Experimental neutron multiplicities and spectral slope parameters are compared with evaporation calculations for the damped $^{165}Ho+{}^{56}Fe$ reaction as a function of E_{loss} for different degrees of energy relaxation of the dinuclear system. These calculations indicate that the popular direct interpretation of the slope parameters in terms of the nuclear temperature of the emitter is poorly justified. Detailed comparisons for two different primary reaction fragment distributions show that the energy partition of the primary fragments is energy-loss dependent and, for small energy losses, far from thermal equilibrium. For $E_{loss} < 100$ MeV, the ratio E_L(Fe-like)/E_H(Ho-like) > 0.5 and for $E_{loss} = 150$ MeV, this ratio is given by A_L/A_H.

Studies of the kinetic energy spectra and multiplicities of light particles emitted in damped heavy-ion reactions are very important for the determination of thermal relaxation times and the degree of energy equilibration in nuclear systems which may initially be far from equilibrium. Experiments have focused on neutron emission[1–4] since the deexcitation of primary fragments from very heavy-ion collisions occurs predominantely by this process. The nucleon exchange mechanism[5,6] predicts rather similar fluxes of exchanged particles in each direction. Hence, the resulting temperatures T of the two interacting nuclei of an asymmetric system can be rather different, especially for small total kinetic energy losses, if the heat conductivity of the interaction zone is small enough. This qualitative expectation of the nucleon-exchange model has been verified by experimental measurements[7–11] of the partition of the total excitation energy in damped reactions. On the other hand, the experimental energy spectra of neutrons from projectile-like and target-like nuclei are rather similar in the respective rest frames, even for asymmetric systems with relatively small energy losses. This result has sometimes been interpreted as a signal of thermal equilibrium of the primary fragments. The purpose of this Communication is to resolve this apparent discrepancy.

The multiplicities of light particles emitted from damped-reaction fragments can be utilized to deduce the primary excitation energies of projectile-like (L) and target-like (H) fragments if one assumes that the particles are evaporated statistically from the two primary fragments of mass numbers A_L and A_H. In the *special* case when the primary fragments are in *thermal* equilibrium ($T_L = T_H$), the average ratio E_L/E_H of the excitation energies of the two fragments is given by a_L/a_H, where $a_L(a_H)$ is the level density parameter of the projectile-like (target-like) fragments. If $a_L = A_L/k_L$ and $a_H = A_H/k_H$,

$$E_L/E_H = a_L/a_H = A_L k_H / A_H k_L \ , \tag{1}$$

and the energy partition is equal to the mass number ratio when $k_H = k_L$. Although the latter case is often discussed in the literature as typical of thermal equilibrium, shell structure in one of the fragments (e.g., of ^{208}Pb in the $^{208}Pb+{}^{86}Kr$ reaction)[10] may favor a more equal equilibrium partition of excitation energy when a_L is approximately equal to a_H.

In the rest frames of the damped reaction fragments, statistical evaporation spectra of neutrons from the respective fragments are given approximately by

$$dN/dE \propto E^n \exp(-E/S) \ , \tag{2}$$

where E is the neutron energy in the center of mass of the emitter and S is the slope parameter deduced by fitting the neutron energy spectrum associated with the projectile-like or target-like fragments. If only one neutron is emitted from each fragment, $n = 1$ and the spectrum is Maxwellian in shape. In addition, the slope parameter S is equal to the temperature T of the residual fragment. However, for a neutron cascade, it has been shown[12] that $n = 0.45$. Previous analyses[1] of neutron energy spectra from the $^{165}Ho+{}^{56}Fe$ reaction have shown that S_L is approximately equal to S_H for total kinetic energy losses ranging from 60 to 200 MeV. At this point it is important to emphasize that the measured slope parameters S_L and S_H are related to the effective temperatures of the respective series of *residual fragments after particle evaporation* and are *not* the temperatures of the *primary fragments* in a damped reaction. This property of spectral measurements is often not appreciated. As will be shown below for the $^{165}Ho+{}^{56}Fe$ reaction, an energy partition $E_H/E_L = A_H/A_L = 2.95$ requires a slope parameter ratio (S_H/S_L) of approximately 2 for a total kinetic energy loss of 50 MeV (see Fig. 1, where the solid line represents a calculation based on an energy partition according to a_H/a_L or A_H/A_L when $k_H = k_L$). Since the experimental slope ratio is near unity, $E_L/E_H > A_L/A_H$, i.e., the primary Fe-like

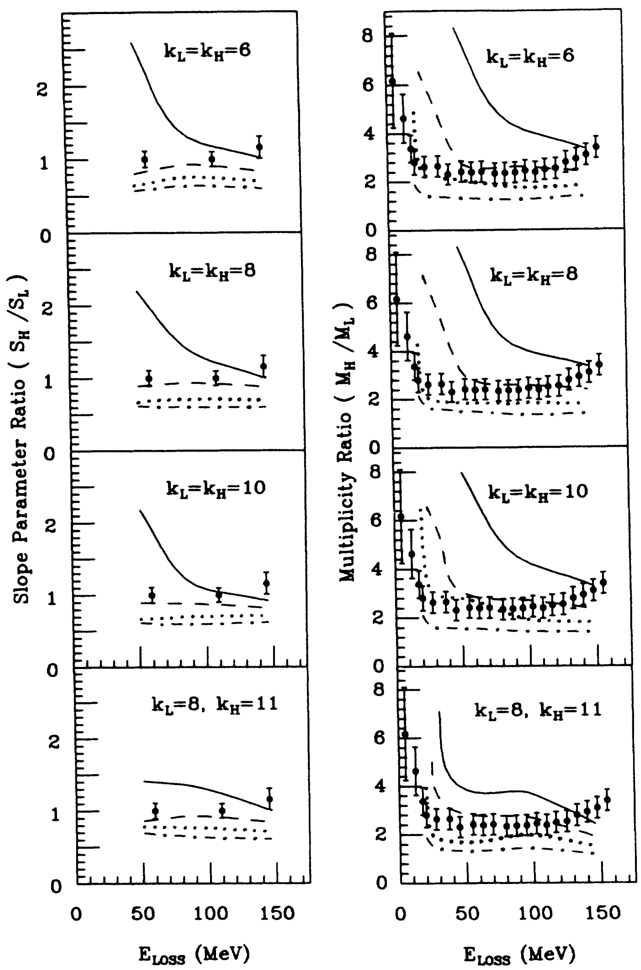

FIG. 1. Comparison of experimental (solid points) and calculated (curves) ratios of the slope parameters and neutron multiplicities of the Ho-like (H) and Fe-like (L) fragments as a function of kinetic energy loss. The four curves represent different partitions of the energy (see Table I) between the two primary fragments. The primary fragment distributions were calculated with the one-body nucleon-exchange model (Refs. 5 and 6). The slope parameter $S_H(S_L)$ has units of MeV. The level density constant $k_H(k_L)$ is defined by $a_H = A_H/k_H(a_L = A_L/k_L)$ and has units of MeV.

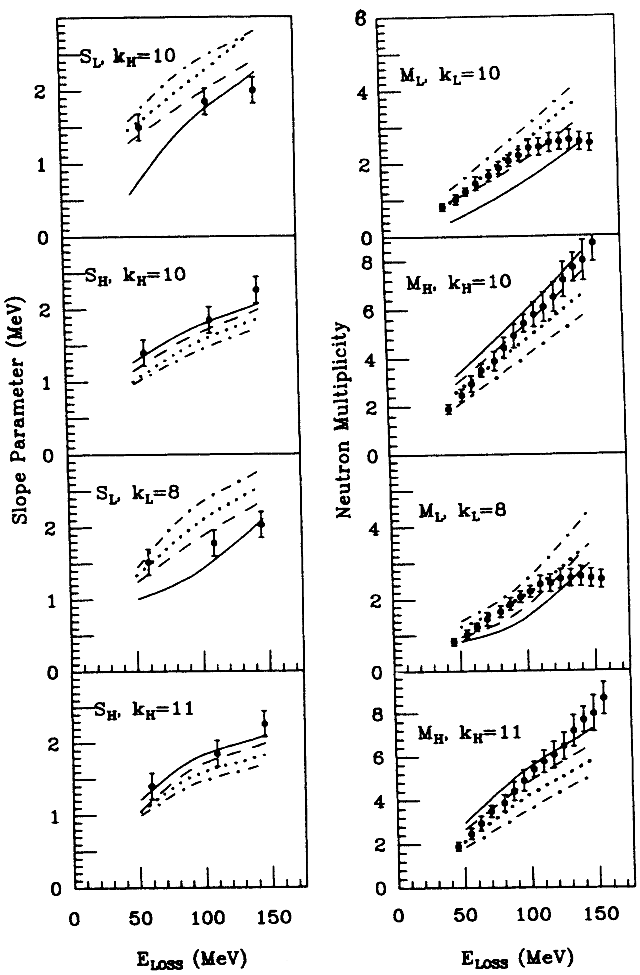

FIG. 2. Comparison of experimental (solid points) and calculated (curves) slope parameters and neutron multiplicities of individual Ho-like and Fe-like fragments as a function of kinetic energy loss. See caption of Fig. 1.

fragments are thermally hotter than the primary Ho-like fragments.

Quantitative comparisons of the experimental neutron multiplicities and spectral slope parameters with model calculations assuming different degrees of energy relaxation of the primary fragments from a damped reaction were performed with the evaporation code PACE.[13] Included in the calculations were neutrons, protons, alpha particles, and gamma rays. The energy-loss dependent primary fragment input distributions for the PACE calculations were generated in two ways. For the majority of the cases depicted, the first and second moments of the primary reaction fragment distribution were calculated with the one-body nucleon-exchange model.[5,6] The spins of the primary fragments predicted by the nucleon-exchange model (NEM) are employed in these calculations. Results employing these primary distributions (NEM) are shown in Figs. 1 and 2. Additional calculations of the above two moments of the primary reaction fragment distribution utilized the experimental secondary reaction fragment distribution[14] corrected for neutron emission.[1] The spins of the primary fragments for these calculations were again those predicted by the nucleon-exchange model. Results from these primary distributions (ESCN) are shown in Fig. 3. It was determined by a series of calculations that sufficient accuracy in the slope parameters and multiplicities was obtained by using only the major part of the two-dimensional Gaussian distribution in N and Z space of the primary reaction fragments. For the highest energy loss, calculations including primary fragments representing 68% of the total distribution agree within statistics with the results obtained using 99.9% of the primary distribution.

Once a primary fragment distribution was selected, a PACE calculation was performed on each of the nuclei in the distribution. The particle spectra and multiplicities for

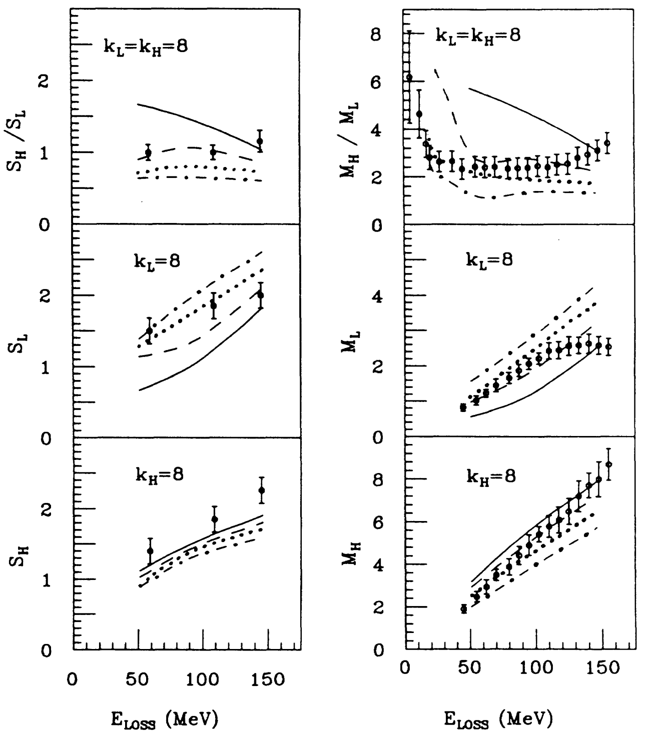

FIG. 3. Comparison of experimental (solid points) and calculated (curves) slope parameters, neutron multiplicities, and their ratios as a function of kinetic energy loss. The primary fragment distributions are deduced from the experimental secondary reaction fragment distributions (Ref. 14) corrected for neutron emission (Ref. 1). The four curves represent different energy partitions of the primary fragments as defined in Table I. See caption of Fig. 1.

each nucleus calculated from PACE were then integrated over the primary fragment distribution to obtain the composite neutron energy spectrum and the multiplicity associated with each primary reaction fragment distribution. The energy spectrum was then fitted with Eq. (2) in order to find the slope parameter of the spectrum. A value of $n=0.5$ was used in the fit since this value of n was used to fit the experimental data.[1] The slope parameter is not very sensitive to the value of n.

Calculations were performed with four different partitions of the total excitation energy between the projectile-like and target-like fragments. This information, along with the k values defining the level densities of the fragments, is summarized in Table I. The major problem with a calculation of this sort is the computer time required. Each calculation was performed as a function of energy loss and took an average of 4.3 CPU days on a VAX 8600. The result of each calculation, however, is an extremely detailed statistical prediction of the observed particle emission spectra and multiplicities for a strongly damped collision.

In Fig. 1 the experimental (solid points) and calculated (NEM) ratios of the slope parameters and neutron multiplicities of the Ho-like (H) and Fe-like (L) fragments are plotted as a function of kinetic energy loss. The four different curves are calculated with different ratios of the energy partition between the two fragments (the magnitudes of the energy partition for the four curves are listed in Table I). As can be seen by the solid curves in Fig. 1, neither the calculated ratios of the slope parameters nor the ratios of multiplicities agree with experimental data for energy losses of less than 100 MeV when one assumes the energy partition to be given by $E_L/E_H=A_L/A_H$. However, the calculated multiplicity ratios agree with the experimental data for $E_L/E_H\approx 0.6$ (data between the dashed and dotted curves) while the calculated slope parameter ratios are consistent with the data when $E_L/E_H\approx 0.5$ (dashed curve). One of the advantages of comparing ratios is that the calculated results are nearly independent of the level density constant $k(a=A/k)$ when $k_L=k_H=6$, 8, and 10 (see the top six frames in Fig. 1). For the large energy losses ($E_{\text{loss}}>100$ MeV), the calculated slope and multiplicity ratios approach the experimental data for an energy partition $E_L/E_H=A_L/A_H$. The results shown in the two bottom frames in Fig. 1 are calculated with different level density constants $k_L=8$ and $k_H=11$. The energy partition of the primary fragments derived from Eq. (1) is listed in Table I for each of the four curves. The solid curve now represents an energy partition $E_L/E_H=k_HA_L/k_LA_H=0.47$. The conclusions one reaches in this case are similar to those discussed above.

The experimental (solid points) and calculated (NEM) slope parameters and multiplicities of the individual Ho-like and Fe-like fragments are plotted in Fig. 2 for $k_L=k_H=10$ and $k_L=8$, $k_H=11$. The energy partition between the two primary fragments deduced from the individual multiplicities is consistent with E_L/E_H being larger than 0.5 for energy losses less than 100 MeV, a result similar to that deduced from the multiplicity ratios. The slope parameters of the individual Fe-like fragments

TABLE I. Summary of the input parameters used in PACE. The quantities E_L and E_H are the excitation energies of the light and heavy fragments, respectively, including the rotational energies; $E_L+E_H=E_{\text{loss}}+Q_{gg}$.

Line	$E_L/(E_L+E_H)$	E_L/E_H	E_H/E_L	$E_L/(E_L+E_H)$	E_L/E_H	E_H/E_L
	($k_L=k_H=6,8,10$)			($k_L=8$, $k_H=11$)		
Solid	0.253	0.339	2.95	0.318	0.467	2.14
Dashed	0.333	0.500	2.00	0.398	0.661	1.51
Dotted	0.413	0.704	1.42	0.478	0.916	1.09
Dashed-dotted	0.493	0.972	1.03	0.558	1.26	0.792

are also consistent with this energy partition. The slope parameters of the individual Ho-like fragments, however, are best described with an energy partition equal to a_L/a_H [see Eq. (1)]. This slight inconsistency in the overall results is not understood. However, as can be seen in Fig. 2, the calculated slope parameter of heavy fragments in an asymmetric system is quite insensitive to the assumed partition of energy due to their large level densities.

The slope parameters and multiplicities calculated for primary fragment distributions deduced from the secondary reaction fragment distributions[14] corrected for neutron emission[1] (ESCN) are compared to experimental data (solid points) in Fig. 3. Calculated results are shown only for the level density constant $k=8$, where the assumed energy partition represented by the different curves are again defined in Table I. For $E_{\text{loss}} < 100$ MeV, the individual multiplicities of each fragment, the multiplicity ratio, the slope parameter ratio, and the slope parameter of the Fe-like fragments are best described by an energy partition $E_L/E_H > 0.5$, a result in very good agreement with the calculations utilizing the primary fragment distributions predicted by the one-body nucleon-exchange model. Again, the slope parameter of the Ho-like fragments is reproduced with an energy partition equal to A_L/A_H.

The energy partition of the primary fragments from the $^{238}U + ^{56}Fe$ damped reaction has been determined[9] in an experiment measuring the peak-to-valley ratio of the sequential fission products. Values of E_L/E_H deduced with this technique, for energy losses in the 40–70 MeV range, are in excellent agreement with the energy partition determined from neutron multiplicity and slope parameter ratios as reported here.

In summary, in order to fit the experimental multiplicity ratios at the smaller energy losses, the present detailed calculations with PACE confirm that the energy partition between the primary fragments is such that E_L/E_H is substantially larger than A_L/A_H, as was shown previously.[7] The multiplicity ratios are consistent with an energy partition E_L/E_H of about 0.6 at $E_{\text{loss}} = 75$ MeV, decreasing to a value near 0.34 at an E_{loss} of 150 MeV. Comparison of the experimental and calculated slope parameter ratios gives an energy partition consistent with the above multiplicity ratio data. Finally, it is important to emphasize that the slope parameter measured by fitting an experimental particle evaporation spectrum with a theoretical expression like Eq. (2) is *not* the temperature of the primary fragment. This fact has often not been realized when reporting results from particle-spectral measurements. Similarly, the populations of excited nuclear states in complex evaporation residues do not reflect directly the compound nucleus temperature, in contrast to assumptions made[15] in the recent literature.

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