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Manifestations of excitation energy equilibrium in deep-inelastic collisions

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The consequences of excitation energy equilibrium between the two partners in a deep-inelastic collision are explored. In this work we calculate the second moment of the excitation energy distribution and demonstrate the effects of the fluctuations on evaporated particle spectra and the correlation created in the numbers of evaporated particles from the deep-inelastic fragments.

[NUCLEAR REACTIONS Studied excitation energy division in deep-inelastic collisions, first and second moments. Calculated influence of fluctuations on evaporated particle spectra, correlations in evaporated particle number. Statistical equilibrium model, Monte Carlo statistical evaporation.]

The equilibration of excitation energy between the partners in a deep-inelastic collision (DIC) appears to occur on a very short time scale. This fast equilibrium seems to be required by the experimental observation that the mean number of evaporated particles from coincident reaction products is indicative of a splitting of the total dissipated energy in proportion to the fragment masses,[1-6] as required by the thermal equilibrium condition. Moreover, this proportionality is found for the entire range of dissipated energy, up to the smallest energy losses[4-6] (i.e., the shortest collision times). Thus the thermalization time must be shorter than the shortest interaction times so that the fragments attain thermal equilibrium while they are in contact. A further check of complete statistical equilibrium can be made by observing statistical fluctuations in the division of the excitation energy between the two fragments.[7] Such fluctuations will have important consequences for the reaction products. The effects of a fluctuating excitation energy division on evaporation spectra and the disguising of pre-equilibrium components have been described recently by Schmitt *et al.*[8] Fluctuations in the excitation energies of the primary reaction products from DIC also must be taken into account in measurements of the isobaric width of the primary fragments.[9-11] The effect of fluctuations on the isobaric widths has been noted but also neglected (e.g., Ref. 11) or treated as a free parameter (e.g., Ref. 10).

In this report we evaluate the magnitude of statistical fluctuations in the energy partition in DIC and explore two avenues through which the calculated fluctuations can manifest themselves: neutron energy spectra and evaporated neutron number. We find that these two observables are complementary in that statistical fluctuations have a large effect on the neutron energy spectra when the mass asymmetry is large, but have a relatively small effect for equal fragments. Fluctuations also introduce a covariance in the number of evaporated nucleons which is most prominent for equal fragments.

The statistical weight of a division of the total excitation energy E between two fragments in statistical equilibrium is proportional to the product of their level densities:

$$P(x)dx \propto \rho_1(x)\rho_2(E-x)dx\,. \tag{1}$$

When the fragments are in equilibrium, then

$$\frac{d}{dx}\ln P(x) = 0 = \frac{d}{dx}[\ln\rho_1(x)] + \frac{d}{dx}[\ln\rho_2(E-x)] = \frac{1}{T_1} - \frac{1}{T_2}. \tag{2}$$

The terms on the right hand side of Eq. (2) are the reciprocals of the fragment's temperatures and their equality immediately requires the excitation energy to divide in proportion to the mass ratio:

$$\frac{E_1^*}{E_2^*} = \frac{x}{E-x} = \frac{A_1}{A_2}. \tag{3}$$

We can estimate the width of the excitation energy distribution by noting that the distribution in (1) is sharply peaked. The expansion of the logarithm about the maximum up to 2nd order gives a Gaussian

$$P(x)dx \propto e^{-(x_0-x)^2/2\sigma^2}, \tag{4}$$

thus

$$\frac{1}{\sigma^2} = \frac{d^2}{dx^2}\ln P(x) = \frac{d}{dx}\left(\frac{1}{T_1}\right)_T + \frac{d}{dx}\left(\frac{1}{T_2}\right)_T = \frac{1}{T^2}\left(\frac{1}{C_{V1}} + \frac{1}{C_{V2}}\right), \tag{5}$$

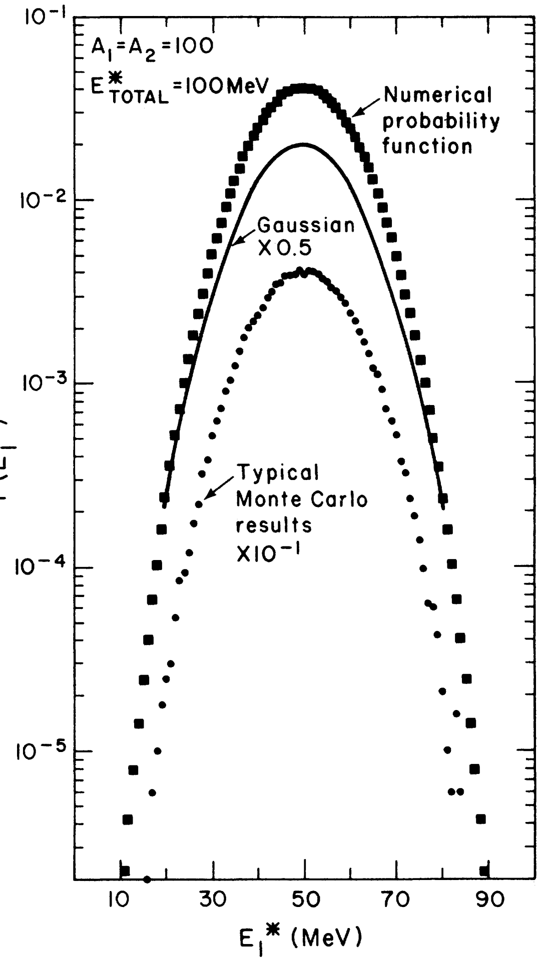

FIG. 1. The excitation energy distribution for one fragment obtained from a numerical calculation (squares), the Gaussian approximation (solid curve), and a Monte Carlo evaporation calculation (points) are shown for comparison.

where C_{V1} and C_{V2} are the heat capacities of the two fragments (for a Fermi gas $C_V = 2aT$ at a temperature T). By substitution we obtain for the width

$$\sigma^2 = 2T^3\left(\frac{a_1 a_2}{a_1 + a_2}\right), \tag{6}$$

where a_1 and a_2 are the level density parameters of the fragments. A comparison of the Gaussian approximation with an analytical calculation from Eq. (1) is shown for a symmetric mass split in Fig. 1. The Gaussian is a good approximation near the peak but is too wide in the tails of the distribution.

A direct way in which any fluctuations in the excitation energy of DIC fragments can be observed is in the energy spectra of evaporated nucleons. For simplicity we will consider only neu-

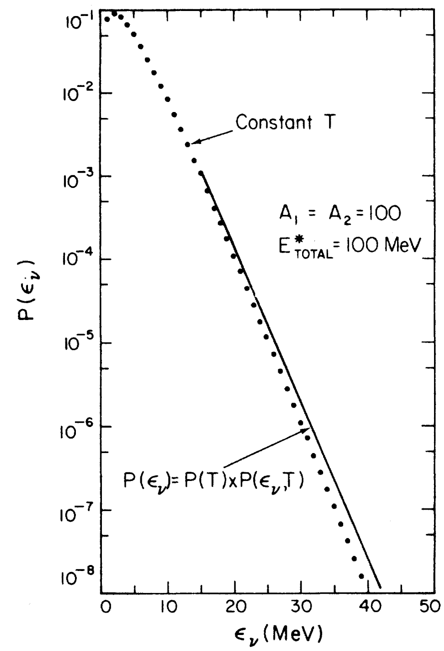

FIG. 2. The neutron energy spectrum is shown for evaporation from a fragment with $A = 100$ at a fixed excitation energy (solid points) and from the same fragment with a fluctuating excitation energy (solid curve).

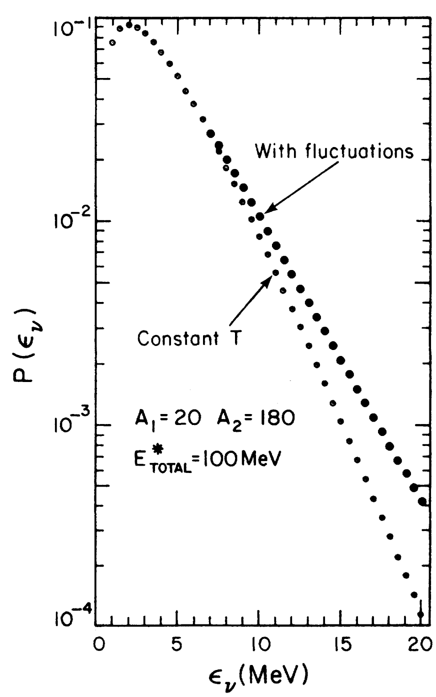

FIG. 3. Similar to Fig. 2, except evaporation is from an $A = 20$ fragment that had been in thermal equilibrium with an $A = 180$ fragment.

tron evaporation. The neutron energy spectrum can be written as

$$P(\epsilon, E^*) = \frac{\epsilon}{E^*/a} e^{-\epsilon/(E^*/a)^{1/2}} , \qquad (7)$$

where ϵ is the neutron energy and the dependence on the fragment's excitation is written explicitly. The neutron spectrum for a fluctuating excitation energy can be calculated by numerically folding Eq. (1) with Eq. (7). The results of such calculations are shown for a symmetric (100:100) and an asymmetric mass split (20:180) with the same total excitation energy (100 MeV) in Figs. 2 and 3. One can see that in the first case the fluctuations have a relatively minor effect on the spectrum. However, for the asymmetric case the magnitude of the fluctuations is comparable to the total excitation energy of the light fragment and therefore produces an important change in the spectrum.[8] These calculations apply to the first nucleon evaporated from the fragments and any comparison to experiment must include second, third, and further neutrons as required to cool the nucleus. This will further modify the shape of the evaporation spectrum.

A less direct, but more dramatic effect of excitation energy fluctuations can be seen in the number of nucleons evaporated from the pair of DIC fragments. An anticorrelation in the excitation energies of reaction partners naturally arises when the total excitation energy is held constant. The covariance of the number of emitted neutrons from DIC partners was investigated with a simple Monte Carlo code. The division of the excitation energy between symmetric fragments ($A = 100$) was either fixed or picked at random in proportion to Eq. (1). For reference, typical results for the E^* of one fragment obtained in the Monte Carlo are shown in Fig. 1. The two fragments were then allowed to emit neutrons until the nuclei had cooled to less than $B_N + 2T'$, where B_N is the liquid drop neutron binding energy and T' is the temperature after emission of the previous neutron. The probability contours for emission of ν_1 neutrons from fragment 1 and ν_2 neutrons from fragment 2 are shown in Figs. 4(a) and 4(b). When the fluctuations are turned on, a strong correlation is introduced and is manifested in the distribution of final product masses.

In summary, we have investigated the implications of complete statistical equilibrium in DIC on the spectra of evaporated particles and the number of evaporated particles from coincident fragments. We have shown that fluctuations in the excitation energy of DIC fragments are large (proportional to T^3) and can strongly affect experimental observables. In particular, for very asymmetric mass splits, the fluctuations are comparable in magnitude to the excitation energy of the light fragment, which increases the probability of evaporating high energy neutrons. This increase is not as strong when the mass split is symmetric. We have also shown that the anticorrelation of the division of the total excitation energy between reaction partners becomes, through the deexcitation stage, an anticorrelation in the evaporated particle number (or final mass of the fragments). The stage has now been set for experimental investigation of the excitation energy fluctuations. In anticipation of the experimental results it would be interesting to see if calculations based on quantal excitations of the giant modes can predict the proper widths of the excitation energy distributions. At present such calculations, including particle transfer, do not accurately reproduce the observed division.[12] The additional agreement of the second moment to the previous agreement of the first moment of the excitation energy distribution would be strong evidence that the DIC fragments are in full statistical thermal equilibrium.

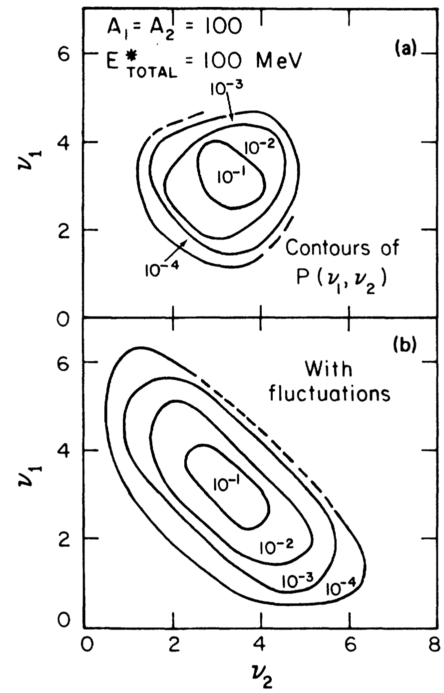

FIG. 4. The results for the number of evaporated neutrons from correlated DIC fragments from the Monte Carlo code are shown (a) for a fixed partition of excitation energy, and (b) for fragments in statistical equilibrium.

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