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Systematics of nonequilibrium neutron emission

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Neutron spectra have been obtained at various angles in ^{12}C, ^{13}C, and ^{20}Ne reactions leading to the ^{170}Yb compound nucleus between 4 and 11 MeV/nucleon above the Coulomb barrier. The energy and angular distributions can be fitted by a moving hot source model. However, this model does not consistently explain other systematic trends obtained by the analysis. The Boltzmann master equation model also does not provide an adequate fit to the data.

[NUCLEAR REACTIONS ^{12}C, ^{13}C, ^{20}Ne, 4–11 MeV/nucleon, nonequilibrium neutron emission systematics.]

In a previous paper[1] (henceforth referenced as NEC), we reported on nonequilibrium neutron emission (NNE) in ^{12}C and ^{13}C reactions on ^{158}Gd and ^{157}Gd targets, respectively. We obtained detailed energy spectra and angular distributions of NNE in coincidence with evaporation residues. Recently, we have obtained additional data at the Oak Ridge Isochronous Cyclotron on neutron emission for $^{12}C+^{158}Gd$ at 192 MeV, and for $^{20}Ne+^{150}Nd$ at 176 and 239 MeV. These data are sufficient to provide stringent tests of the validity of various models of NNE; a comprehensive list of such models is presented in NEC (Refs. 35–51). We present here a comparison with two models: (1) the Boltzmann master equation model[2] (BME) and (2) a "hot spot" model of the moving-hot-source type presented in NEC. We will show that neither of these models is completely adequate for describing all aspects of the systematic trends observed in the data.

Figure 1 presents the nonequilibrium neutron multiplicity (obtained using the moving-hot-source model to fit the data[1]) for the various reactions as a function of the energy per nucleon above the Coulomb barrier $\epsilon=(E_{\rm c.m.}-V_C)/\mu$. ($E_{\rm c.m.}$ is the c.m. bombarding energy, V_C the Coulomb barrier, and μ the reduced mass.) We note the similarity between the results of the three different reactions when the multiplicity is plotted as a function of ϵ. The slightly

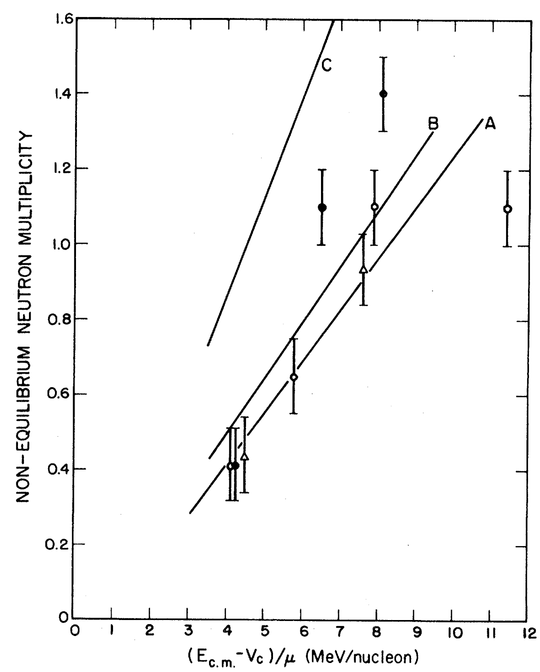

FIG. 1. Nonequilibrium neutron multiplicity as function of energy per nucleon above Coulomb barrier. Hollow circles: ^{12}C data; full circles: ^{13}C data; triangles: ^{20}Ne data. The lines marked *A*, *B*, and *C* are obtained from the BME model for ^{12}C, ^{13}C, and ^{20}Ne, respectively.

higher values for NNE in the ^{13}C reaction (10–20%) may be due to a small breakup contribution[3] in which the ^{12}C fragment resulting from the breakup is absorbed by the target nucleus. ^{13}C is especially susceptible to such reactions because of the low (4.9 MeV) binding energy of the last neutron. The lines present multiplicities obtained using the BME model,[2] if we assume the number of excitons to be equal to the number of particles in the projectile. This model predicts the ^{20}Ne reaction to have a much higher NNE multiplicity compared to the ^{12}C and ^{13}C reactions, contrary to our observations. This conclusion is independent of the parameters used in the BME model calculations. We note that for experimental values of multiplicities, only relative values should be considered; the absolute values depend strongly on the model used to extract them from the experimental data.[1]

Figure 2 presents values of T_{NE}, the temperature of the moving-hot source[1] obtained from a fit to the data. The results of Awes *et al.*,[4] obtained for proton emission systematics, are also shown in Fig. 2. We find that, in our case, T_{NE} is relatively constant as function of ϵ, while in Ref. 4 the temperature was found to increase gradually with the energy per nucleon above the Coulomb barrier. There are several possible reasons for this difference. (1) There is a significant difference between the high energy tails of proton and neutron spectra.[5] (2) The data of Ref. 4 are inclusive; our data were obtained in coincidence with evaporation residues. (3) The proton data[4] extend to much higher particle energies than our neutron data; the temperature in Ref. 4 is determined mainly by particle energies above 30 MeV. The full lines in Fig. 2 present temperatures obtained from the nonequilibrium neutron spectra of the BME model. When comparing these temperatures to T_{NE}, we note that they are not identically defined: T_{NE} is defined in the frame of a hot source moving with a velocity v_{NE} in the lab system (also obtained from the fit[1]) whereas the BME temperature is determined in the center-of-mass frame. In order to make a valid comparison, we have transformed our spectra to the c.m. system and integrated over all angles. The slope of the resulting spectrum yields an effective temperature approximately 25% larger than T_{NE}, but still significantly lower than the BME temperature.

The success of the moving-hot-source model in fitting energy spectra and angular distributions raises questions of consistency, and we examine these below with reference to the velocities of the hot source extracted from our data.

We consider the collision in the frame of reference of the target (which, just prior to contact, is moving with a velocity v_T in the lab system). We denote $v_{ob}^{c.m.}=\sqrt{2\epsilon}$, the relative velocity at the Coulomb barrier. In Fig. 3, we plot $v_{NE}^{T}=v_{NE}-v_T$ (the hot-source velocity in the target frame of reference), as a function of $v_{ob}^{c.m.}$ for the various systems we have studied. We find that the data are compatible with a linear correlation of the form $v_{NE}^{T}=\lambda v_{ob}^{c.m.}$, $\lambda=0.24$. This is reminiscent of collisions in which there is a constant ratio between the projectile mass and the final product (i.e., hot spot) mass: Denoting M_{HS} the mass of the hot spot and M_P the projectile mass, momentum conservation (considered in the target frame) leads to the expression

$$M_{HS}=fM_p v_{ob}^{c.m.}/v_{NE}^{T} \quad , \tag{1}$$

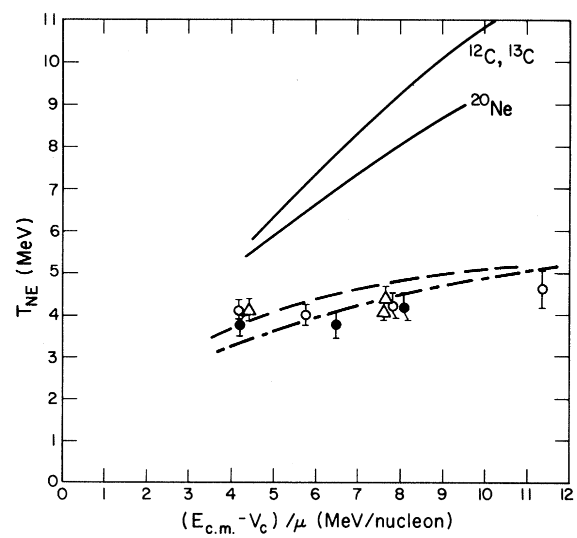

FIG. 2. NNE temperature as function of energy per nucleon above Coulomb barrier. The individual points have the same meaning as in Fig. 1. The dashed line was taken from Ref. 4. The full lines are results of BME calculations. The dot-dashed line was calculated using Eq. (3).

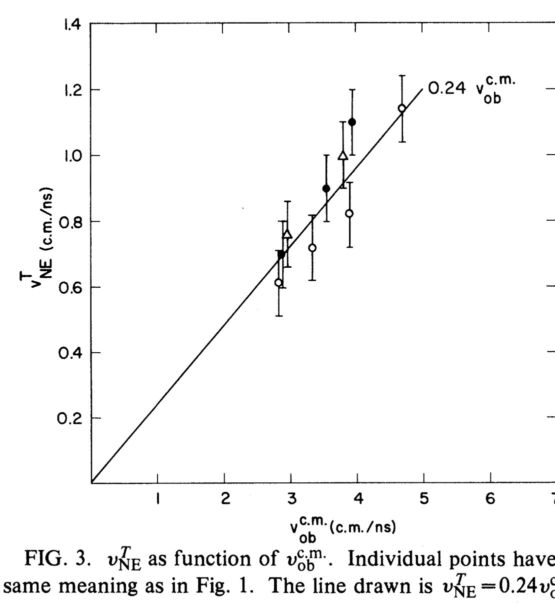

FIG. 3. v_{NE}^{T} as function of $v_{ob}^{c.m.}$. Individual points have same meaning as in Fig. 1. The line drawn is $v_{NE}^{T}=0.24v_{ob}^{c.m.}$.

where f is the fraction of nucleons in the projectile contributing to the hot spot. Inserting the observed correlation between $v_{\rm ob}^{\rm c.m.}$ and $v_{\rm NE}^{T}$, we find that the hot spot is approximately four times larger than the number of nucleons in the projectile producing it.

We calculate the temperature of the hot spot by assuming that the kinetic energy lost during the collision forming it is converted into its excitation energy E_x.

$$\begin{aligned} E_x &= \tfrac{1}{2} f M_p (v_{\rm ob}^{\rm c.m.})^2 - \tfrac{1}{2} M_{\rm HS} (v_{\rm NE}^{T})^2 \\ &= \tfrac{1}{2} M_{\rm HS} (v_{\rm NE}^{T})^2 (1/\lambda - 1) \ , \end{aligned} \qquad (2)$$

$$\begin{aligned} T_{\rm HS} &= (k E_x / M_{\rm HS})^{1/2} \\ &= [(k/2)(1/\lambda - 1)]^{1/2} v_{\rm NE}^{T} \ , \end{aligned} \qquad (3)$$

where k is usually taken as 7–9, but should probably be taken as 14.6 for bulk phenomena.[6] Consequently, we expect $T_{\rm HS}$ to increase proportionally to $v_{\rm NE}^{T}$, which does not seem to be the case for our results of $T_{\rm NE}$. The dot-dashed line in Fig. 2 is obtained from (3) using $k = 14.6$, $\lambda = 0.24$. It underestimates $T_{\rm NE}$ at the lowest energies and does not seem to be consistent with the flat trend of T_N in this energy range.

Summarizing, we find that the BME model does not predict correctly the observed projectile and bombarding energy dependence of the NNE multiplicities and temperatures. A simple hot-spot model fits the energy and angular dependence of NNE, and provides a reasonable estimate of the temperature; however, the model does not accurately predict the temperature dependence on the bombarding energy. It is yet to be determined, in future more detailed theoretical studies, whether the moving source model is just a convenient parametrization or whether it has a more profound physical justification.

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