Pre-equilibrium emission in heavy ion reactions

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Continuous spectra of light particles from heavy ion induced reactions with velocities extending to values above the beam velocity are analyzed in terms of the generalized exciton model. Data are found to be reproduced by model calculations with only one individually adjustable model parameter: the number of initial degrees of freedom n_0. This quantity is energy dependent in contrast to light ion induced reactions.

[NUCLEAR REACTIONS ^{40}Ca(^{6}Li,c)X, $c=p-\alpha$, $E=156$ MeV, ^{165}Ho(^{20}Ne, n + evaporation residues), $E=220$, 290, 400 MeV; calculated spectra for different angles.]

There has been recent interest in the emission of light fast particles in heavy ion induced nuclear reactions.[1] While at very forward angles a component in the spectra with beam velocity gives a hint to breakup processes,[2,3] the reaction mechanism responsible for the remaining yield in the continuous spectra is not well understood. It has become very popular to fit the energy spectra by Maxwell formulas assuming a moving frame. This procedure yields T parameters, similar to the nuclear temperature of a compound nucleus, which are much larger than compound nucleus temperatures. In most cases the frame velocity is half of the beam velocity.[4,5] It is hard to believe that at energies of some tens of MeV/nucleon a part of the target nucleus is cut from the target nucleus to form a nuclear fireball. This is supported by the experimental findings of Awes *et al.*[6] Therefore, to fit Maxwellians seem to be more a parametrization of data. However, systematic studies[6-8] of these parameters may lead to physical understanding.

Another possibility is to invoke models which have been successful in interpreting light ion induced reactions. Especially semiclassical models like the time dependent approaches based on master equations seems to be well suited because of their transparency.

The Harp-Miller-Berne model which treats the equilibration in terms of the occupation numbers of small energy bins has been extended by Blann[9] to heavy ion induced reactions. In this extension it is assumed that fusion of the target-projectile nucleus is time dependent (coalescing phase). The projectile nucleus acts as a donor and the target nucleus as an acceptor. The energy of the donor nucleons is distributed by a function, depending on the model parameter n_0 which represents the degrees of freedom. During the coalescing phase already equilibration, as well as fast particle emission, takes place. It has been shown that agreement between data and model calculations can be achieved only for bombarding energy dependent n_0 values.[7,10] The meaning of this behavior is at the moment not well understood.

The work of Otsuka and Harada[11] is along similar paths. They treat the equilibration process in the framework of the exciton model starting from the following system of master equations:

$$\frac{\partial P(\mathrm{p},\mathrm{h},t)}{\partial t}=\lambda_+(\mathrm{p}-1,\mathrm{h}-1,E)P(\mathrm{p}-1,\mathrm{h}-1,t)+\lambda_-(\mathrm{p}+1,\mathrm{h}+1,E)P(\mathrm{p}+1,\mathrm{h}+1,t)+[\lambda_+(\mathrm{p},\mathrm{h},E)+\lambda_-(\mathrm{p},\mathrm{h},E)+\lambda_c(\mathrm{p},\mathrm{h},E)]P(\mathrm{p},\mathrm{h},t)\ , \tag{1}$$

with an initial condition at time $t=0$: $P(\mathrm{p,h},0)=\delta_{\mathrm{p},1}\delta_{\mathrm{h},0}$ and with $E=E_\mathrm{p}/A$. Every time Δ, one nucleon carrying the energy E is added to the coalescing system. Here, the model parameter is the time Δ which was found from the analysis of 114 MeV ^{14}N + ^{181}Ta data to be $\Delta=3.0\times10^{-23}$ s. Thus the total fusion process takes place at 4.2×10^{-22} s. This value is nearly identical with Blann's result for 104 MeV ^{16}O + ^{197}Au (Ref. 9). For higher bombarding energies Blann obtained shorter fusion times which seems to be natural because of the higher velocity of donor nucleons. However, for smaller values of Δ the spectra become less steep. This is in contrast to experimental findings.

In the work of Yoshida[12] the two coalescing nuclei are treated as two cubes containing Fermi gases. The separating wall is suddenly removed, thus leading to nuclear excitations and in a natural way to an initial distribution $P(n_0,t=0)$. The relative velocity between the two cubes is assumed to be zero. This assumption may probably restrict the approach to relatively small bombarding energies. The calculations reproduce only gross features of data from ^{40}Ca + ^{58}Ni and ^{40}Ca + ^{40}Ca for 50–70 and 42–57 MeV bombarding energy, respectively.

The only attempt to reproduce angular distributions in the framework of the hybrid model[4] with the fast particle approach[13] fails at angles smaller than 40°.

In this contribution we also start with the master equation (1) but use an initial energy dependent exciton number n_0: $P(n,t=0)=\delta_{n,n_0}$.

In light ion induced reactions it has been shown that n_0 is equal to the number of nucleons in the projectile plus 2, i.e., the first projectile-target nucleus interaction leads to additonal 1p-1h excitation.[14] The ^{6}Li nucleus as projectile seems to act as a cornerstone for understanding what may happen as the projectile mass increases. In the case of ^{6}Li induced reactions agreement between data and calculation could not be achieved for n_0= 7p + 1h (Ref. 15) (Fig. 1). However, ^{6}Li is the weakest bound nucleus. The $\alpha+d$ threshold is only 1.47 MeV. It seems therefore natural to assume a breakup of $^6\text{Li}\rightarrow\alpha+d$ with two separate interactions of both fragments with the target nucleus leading to a 2p+2h excitation or n_0= 8p+2h. The shapes of energy spectra of particles (protons to α's) emerging from 156 MeV ^{6}Li + ^{40}Ca reactions are well reproduced by assuming this n_0 value (Fig. 1). We therefore expect for even heavier projectiles larger n_0 values. They should be energy dependent because with higher bombarding energies more fragments may be produced.

To test this assumption we have analyzed spectra of fast neutrons measured in coincidence with evaporation residues (ER) from ^{20}Ne + ^{165}Ho reactions. Data are available[10] for 220, 292, and 402 MeV. At these high bombarding energies it is important to use a good estimate for the residual interaction. For the present calculations we have used the transition rates entering Eq. (1) from Ref. 16:

$$\lambda_+(n,E)=\frac{n!}{k}\sum_{j=0}^{6}\frac{j!a_jE^j}{(n-1+j)!}\ , \qquad (2a)$$

$$\lambda_-(n,E)=\frac{(n-1)!\text{ph}(n-2)}{k(gE)^2}\sum_{j=0}^{6}\frac{j!a_jE^j}{(n-3+j)!}\ , \qquad (2b)$$

with parameters a_j obtained from nucleon-nucleon cross sections in nuclear matter up to 1 GeV and $g\approx A/13$ MeV is the single particle state density and $k=4$ as usual. The emission rate has been calculated from detailed balance. The linear momentum dissipation has been considered in the recursive approach of Mantzouranis[17] but assuming as initial angular distribution an exponential with the same slope parameter as in previous work.[18] Secondary chance emission in the preequilibrium phase has been found to be negligible.

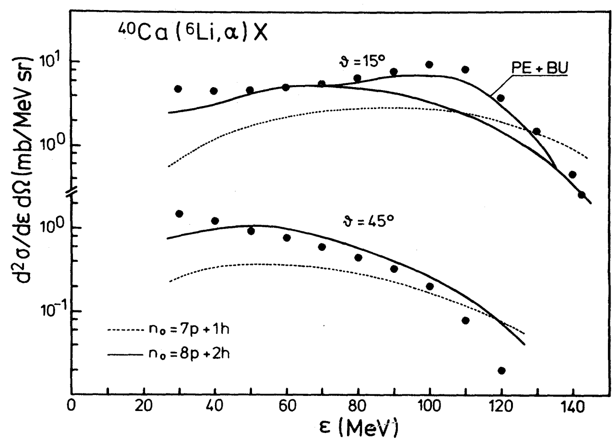

FIG. 1. Spectra of α particles from ^{6}Li + ^{40}Ca reactions at 26 MeV/nucleon (Ref. 15). The model calculations for n_0= 7p + 1h and 8p + 2h are shown as dashed and solid lines, respectively. The sum of exciton model and breakup distorted-wave Born approximation calculation (Ref. 15) is also shown at the forward angle.

We found best agreement with n_0= 22p + 2h, 25p + 5h, and 30p + 10h for bombarding energies of 220, 290, and 400 MeV, respectively. In Figs. 2 and 3 spectra for the two higher beam energies are shown together with calculations. Evaporation calculations[10] using the code JULIAN are also shown. Altogether, the agreement is surprisingly good. To stress the point once more: The only parameter individually adjusted is n_0. Proton spectra from ^{20}Ne + ^{197}Au at 400 MeV have also been best reproduced by n_0= 30p + 10h (Ref. 19). This target independence is confirmed by the findings of Fulmer *et al.*[20]

In the calculations only up to 16 residual interactions have been taken into account. While for the two smaller bombarding energies this seems to be a good approximation, it becomes less justified at higher bombarding energies. How-

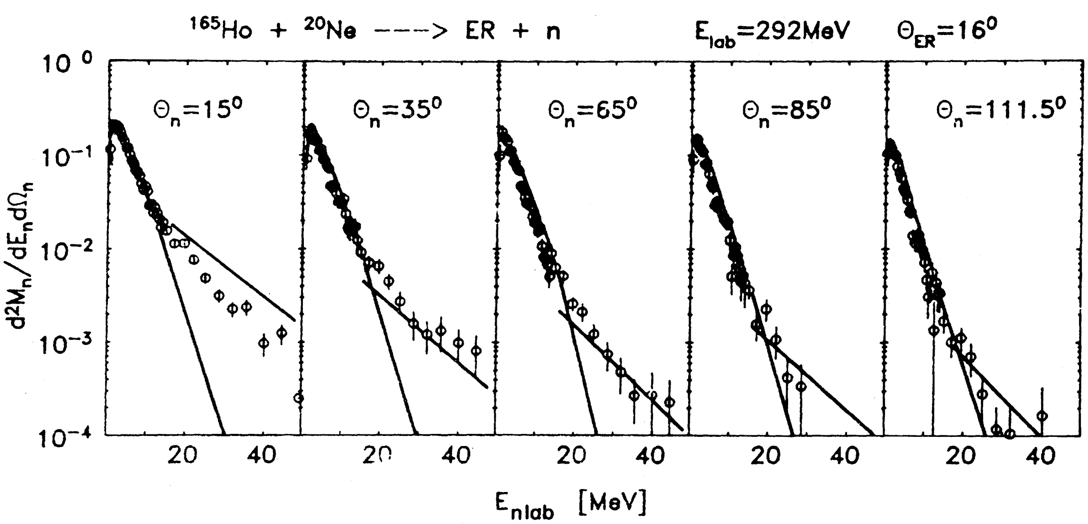

FIG. 2. Neutron multiplicities measured at the indicated angles in coincidence with evaporation residues (ER) are compared with compound nucleus (low energy part) and exciton model calculations (high energy part, solid line) assuming n_0 = 25p + 5h.

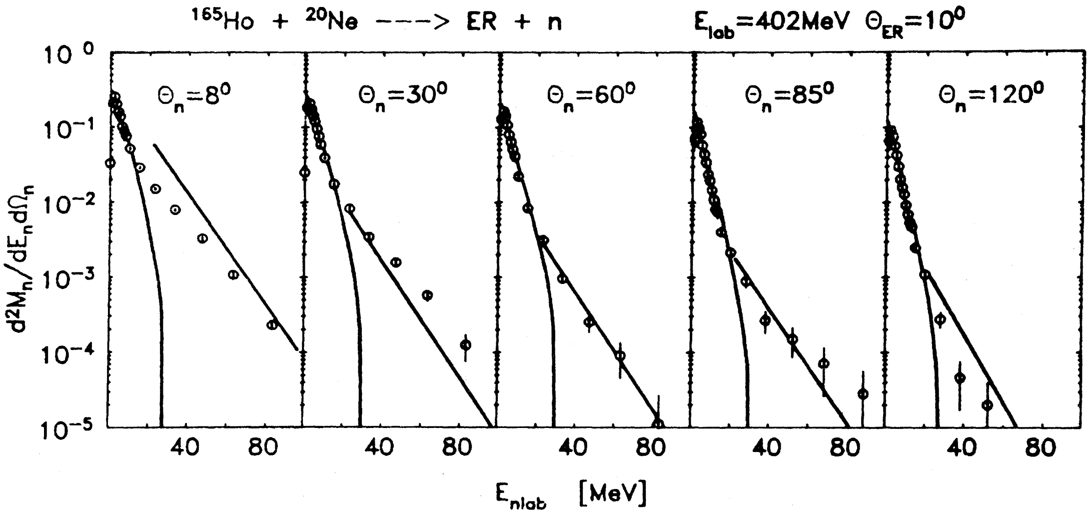

FIG. 3. As Fig. 2 but for a different bombarding energy and $n_0=30p+10h$.

ever, contributions from higher interaction numbers to the cross section are hidden under the compound nucleus part of the spectra.

To summarize, we can say that the generalized exciton model[13,14] is able to reproduce spectra of fast nucleons from heavy ion induced reactions. The number of initially participating excitons increases with increasing bombarding energy. The onset for this effect seems to be around 3.5 MeV/nucleon above the barrier coinciding with the value up to which full momentum transfer occurs in ^{16}O induced reactions.[21] The angle dependent exciton model analysis is a tool to distinguish between precompound and other reaction mechanisms. As an example, the data from $^{14}N + ^{181}Ta$ at 115 MeV previously analyzed with Maxwellians leading to angle dependent T parameters[22] show a beam velocity component when a precompound contribution is subtracted.

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