Critical energy deposit in heavy ion complete fusion

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In the framework of an l-window model for complete fusion reactions within a sharp cutoff approximation, the problem of the maximum excitation energy which can be deposited in a compound nucleus is discussed. Predictions about the spin distribution of the compound nucleus are compared with the conclusions of a recent analysis of the $^{28}Si+^{28}Si$ fusion reaction.

Among the most interesting problems raised by recent experiments with heavy ions in the energy range 10–100 MeV/nucleon, an important role is played by the question of limitations on the complete fusion process.

Recently, phenomenological analysis of the vanishing of the fusion process has been presented[1] in terms of a critical amount of energy (and, consequently, of a maximum excitation energy per nucleon) which can be deposited in the fused system. The "most probable" excitation energy of the fused system (in the case of central collisions) has been determined[1] from the recoil velocity v_R with the assumption that direct particles escape with projectile velocity and that only a part of the nucleons of the projectile fuse with the target. Therefore, the excitation energy per nucleon could be easily deduced from the experimental data.

The effect of a low-angular-momentum window on the average value of the angular momenta contributing to fusion has also recently been discussed.[2] The calculations are presented in the frame of a macroscopic model for heavy ion fusion where the existence of an l window was discussed in comparison with time-dependent Hartree-Fock predictions.[3]

In this Brief Report we want to show the results of a very simple phenomenological model,[4] already used in the analysis of fusion reactions above the Coulomb barrier. Comparison with the model of Ref. 2 will be given in the case of $^{28}Si+^{28}Si$ fusion reaction.

To interpret the vanishing of fusion cross section with increasing bombarding energy, we supposed that the excitation energy of the compound system is shared between a rotational part and an intrinsic part, and we determined[4] a lower cutoff l_{min} by the following prescription: To the complete fusion process, l values can contribute only for which the average intrinsic energy per excited nucleon satisfies the condition $(E^*-E_{rot})/n_{ex}\leq\varepsilon$, where n_{ex} is the number of excited nucleons evaluated in the Fermi-gas model, $\varepsilon=\frac{3}{5}(B/A)$, and B/A is the mean binding energy per nucleon.

This amounts to say that the complete fusion will be suppressed for all l values which do not lead to a bound state in the final A^* nucleus. In other words, it is assuming that the completely fused system (characterized by total mass, charge, energy, and angular momentum) has reached equilibrium with respect to all the internal degrees of freedom. The fusion cross section can therefore be evaluated in a sharp cutoff approximation as

$$\sigma_{fus}=\frac{\pi\hbar^2c^2}{2m_N A_{red}E_{c.m.}}\times[l_{max}(l_{max}+1)-l_{min}(l_{min}+1)]\ ,$$

where the upper limit of the angular momenta contributing to fusion has been taken to be the lowest among those given (for any $E^*=E_{c.m.}+Q$) by the "population line," the yrast line, and the liquid-drop model limitation.[5]

A rigid-body moment of inertia has been used in the calculation of the yrast line. Using this simple idea, one can easily calculate the maximum amount of excitation energy (E^*_{max}) which can be deposited in the fused system as the closing point of the l window in the (l,E^*) plane. Therefore, the excitation energy per nucleon, $\varepsilon^*=E^*_{max}/A$ (where A is the mass number of the compound system), can be deduced for a given fusion reaction. In this way the interpretation of the experimental data is made compatible with the existence of a window in the l values contributing to fusion.

The results are reported in Fig. 1 for a selected number of reactions as function of the compound system mass. The trend is consistent with that reported in Ref. 1. It is worthwhile to note that different reactions leading to the same compound nucleus can have a quite different Q value (as much as about 100 MeV). Therefore, one can get the excitation energy per nucleon, which can differ by about 1 MeV in the larger-mass region. This range of variation is qualitatively shown in Fig. 1 as a hatched area. On that account one can predict, within this simple model, a maximum energy deposit of the order of 250 and 500 MeV for compound systems with $A\simeq 50$ and $A\simeq 200$, respectively.

Different predictions have been made[6] as well as attempts to systematize the experimental results,[1,7] but recent data[8] seem not to be in good agreement with the much larger values predicted in Refs. 6 and 9.

The presence of a low l cutoff should imply a modification of the average l contributing to the fusion process. The difference between the two average values with and without the l window is shown in Fig. 2 as a function of the c.m. energy for the reaction $^{28}Si+^{28}Si$. In

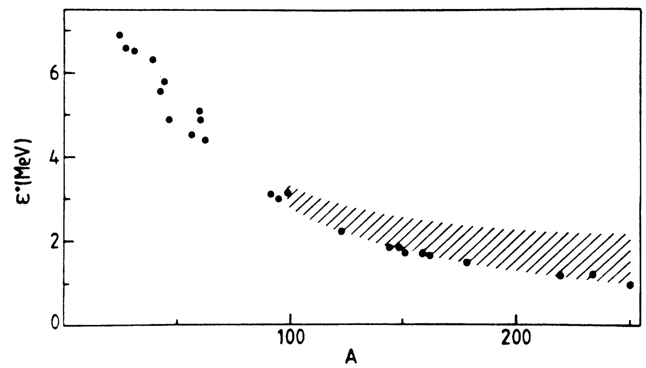

FIG. 1. Maximum amount of the excitation energy per nucleon which can be deposited in fused systems as a function of its mass A. Hatched area accounts for Q-value differences in reactions leading to the same compound systems.

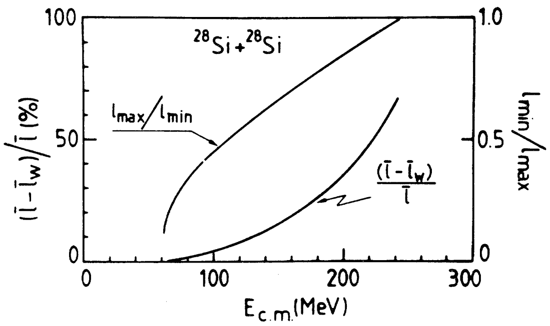

FIG. 2. Effect of the presence of a low l cutoff on the average values of l contributing to fusion. $\bar{l}_w$ and $\bar{l}$ are the average values of the l distribution with and without the window.

the same figure the corresponding ratio l_{min}/l_{max} is also reported.

In the neck model for the fusion reactions, still in the frame of a sharp cutoff approximation, the results obtained by Hong *et al.*[2] are very similar. It is worthwhile to note that our model and that of Refs. 2 and 3 predict the opening of the low l cutoff through different mechanisms. We fix l_{min} as a consequence of the prescription described above, while in Refs. 2 and 3 it is assumed that the low l cutoff is produced by a sudden neck snapping.

One should also remark that no adjustable parameter is contained in our model which gives, in spite of the crudeness of the assumption, predictions in qualitatively agreement with the experimental findings and a quite good evaluation of the fusion cross sections in a wide range of cases.[10]

In conclusion, the (ε^*, A) plane can be divided into two regions: the lower, which allows for complete fusion, and the upper, which is forbidden. In spite of the fact that no decisive conclusion can be drawn from the experimental data, our results, as well as those of Ref. 2, still leave open the possibility of a severe limitation in the l values contributing to the fusion process.

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