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FORMATION OF A DINUCLEAR COMPLEX IN COLLISIONS BETWEEN LIGHT NUCLEI AND ENTRANCE CHANNEL LIMITATIONS TO FUSION

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INTRODUCTION

Entrance channel models for fusion postulate that conditions for capture by the attractive nucleus-nucleus potential determine whether two colliding nuclei will fuse.[1-3] These models, which also allow for kinetic energy and angular momentum dissipation in the collision prior to capture, can account for measured fusion cross sections both at low and high bombarding energies. The basic assumption made in these models is that capture is tantamount with fusion. This premise has been questioned before and it was pointed out that capture does not necessarily lead to fusion.[3,4] Experimental data on binary products from collisions between heavy nuclei show large cross sections for fission-like products that originate in nucleus-nucleus capture without the nuclei actually fusing.[5]

A model for fusion of light nuclei has been proposed recently[6] wherein fusion progresses through nucleus-nucleus capture via a dinuclear stage which acts as a doorway to fusion. While this model accounts for the fusion cross sections, it makes no attempt at predicting observables associated with the non-fusion part of the captured flux. We believe that a study of products from the decay of the dinuclear complex into non-fusion channels can provide a stringent test for such a model. In this contribution we describe a model which addresses both the binary decay and the fusion of a dinuclear complex formed in the collision and compare the model predictions with data. Accompanying contributions discuss the formalism which is used to describe the evolution of the dinuclear complex[7] and present new data which provide information that helps justify the approximations made in applying this model.[8]

THE DATA

In a letter published thirteen years ago[9] Wylcinski pointed out the possible existence of nuclear orbiting and suggested experiments to find it. Figure 1 taken from that article shows that the place to look for the products from nuclear orbiting is near 180 degrees. Studies of binary reaction products at backward angles have indeed uncovered substantial yields that were interpreted as nuclear orbiting products.[10-13] Typical Q-value spectra for fragments with masses near those of the projectile and target emitted at backward angles are shown in Fig. 2. The most probable Q-values of these spectra were found to be independent of detection angle and the yields associated with this process have a $1/\sin(\theta)$ angular distribution in the center of mass (isotropic emission probability). The dependence of the most probable Q-values on bombarding energy

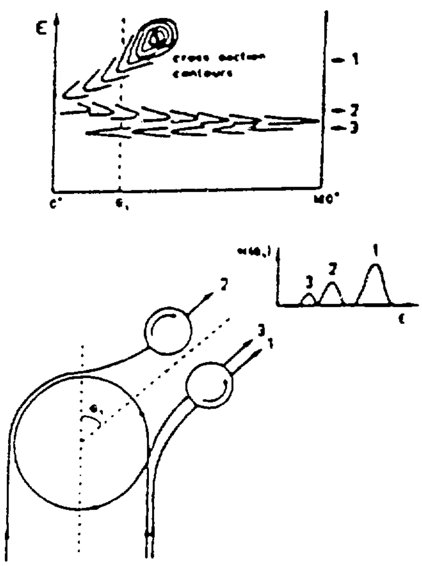

Fig. 1

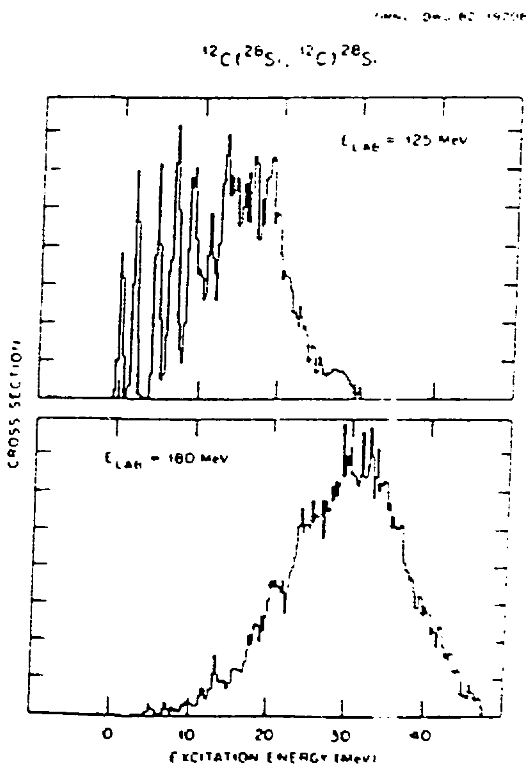

Fig. 2

was measured and is shown in Fig. 3 for two outgoing channels from $^{28}Si + {}^{12}C$ collisions.[10] In this figure we plot the most probable kinetic energies (derived from the Q values) as a function of center of mass incident energy. These figures show an initial rise with incident energy, followed by an apparent saturation. These results can be interpreted in terms of the formation and decay of a long lived rotating dinuclear complex: The initial kinetic energy has been fully damped (converted into excitation of the fragments). Therefore, the final kinetic energy of the fragments at asymptotic separation must be equal to the sum of potential and rotational energies stored in this system. The rotational part introduces the linear dependence on bombarding energy and a simple interpretation of the saturation seen in Fig. 3 stipulates that at some bombarding energy a value of orbital angular momentum is reached, after dissipation, beyond which formation of a dinuclear complex is not allowed due to centrifugal repulsion. An alternative interpretation of these data as compound nucleus decay products has been ruled out because of the large magnitude of these cross sections[10] and evidence for strong memory of the entrance channel.[11] What we have found here is a limiting angular momentum for the process of nucleus nucleus capture. The $^{28}Si + {}^{12}C$ potential shown in Fig. 4 is taken from Ref. 3 (with only slight changes) and it accounts well for the kinetic energy saturation seen in the data of Fig. 3. It is now obvious that if indeed the models we discussed above for entrance channel limitation and our interpretation of the orbiting data are correct the fusion data for the same system must also show the same limiting angular momentum.

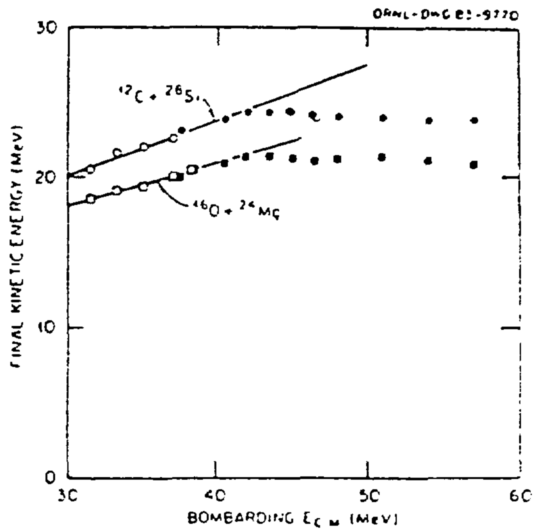

Fig. 3

Fusion cross sections for $^{28}Si + {}^{12}C$ were measured using ^{28}Si beams with energies up to 8.5 MeV/nucleon. In these measurements evaporation residues were fully identified (A and Z) and measured velocity spectra were subjected to a full kinematic analysis. Details of these measurements and results of the analysis are discussed in an accompanying contribution.[14] Shown in Fig. 5 is a

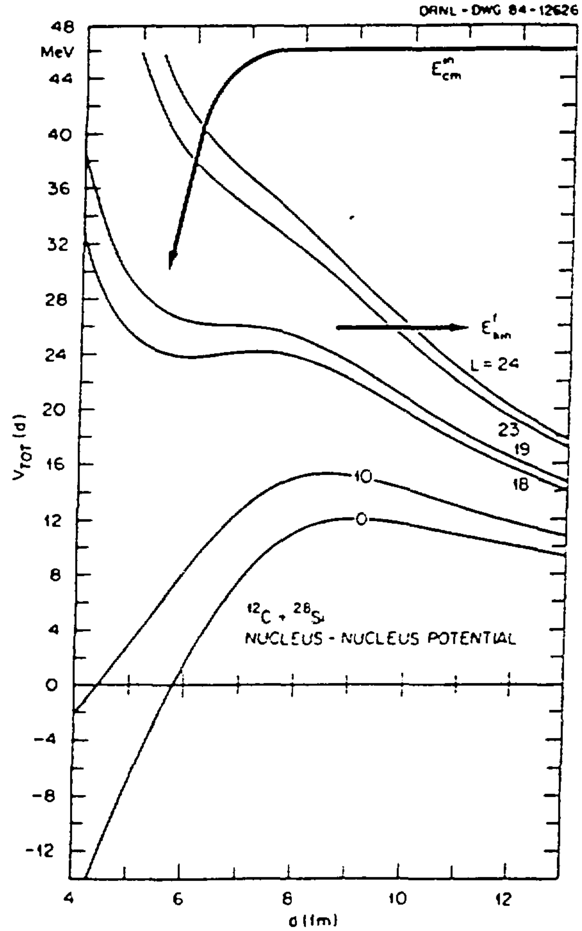

Fig. 4

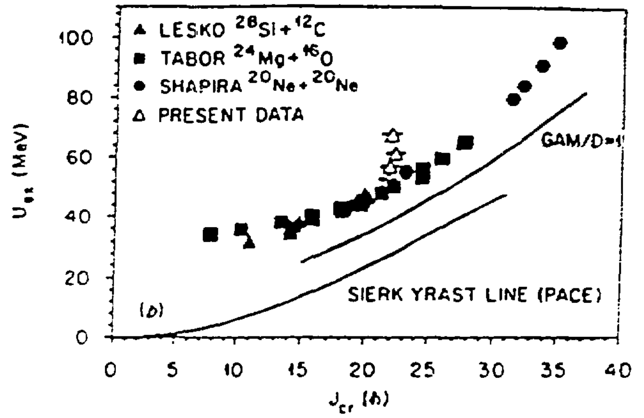

Fig. 5

summary of fusion data for several systems leading to the same compound nucleus (^{40}Ca). The plotted values of maximum angular momentum for fusion were derived from the measured fusion cross sections using the sharp cutoff approximation. There is a very clear signature for an entrance channel limit in ^{28}Si + ^{12}C and the critical angular momentum of J = 23 is precisely the same value one obtains when using the potential shown in Fig. 4. These data show clearly that the fusion and the orbiting cross sections are limited by the same angular momentum value and may therefore be determined by the same entrance channel potential.

THE MODEL

The pertinent features of a model that describes orbiting and fusion in terms of the formation of a long lived dinuclear complex and its subsequent decay by binary fragmentation are shown in Fig. 6. The colliding ions can be trapped into the pocket of the entrance channel potential and a rotating dinuclear complex (DNC) is formed. The DNC evolves through the exchange of nucleons to different dinuclear configurations. At each stage of its evolution there is a finite probability for the DNC to decay into two fragments. That

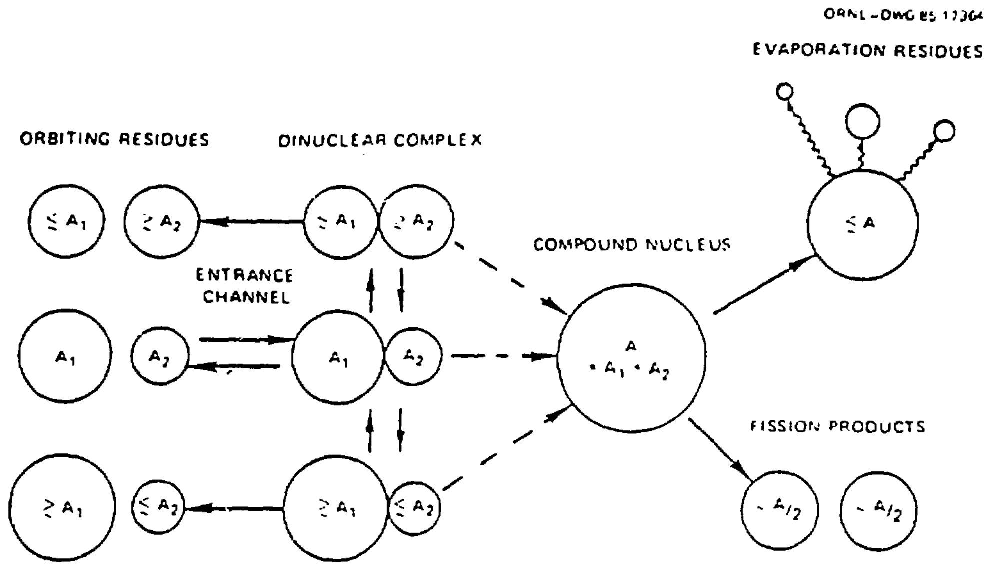

Fig. 6

part of the flux which does not decay into dinuclear channels (two separate nuclei) ends up fusing. The details of the extended diffusion model used to describe the evolution of the DNC appear in Ref. 7. What I wish to emphasize here are the assumptions made. (1) The dinuclear complex evolves mainly via nucleon exchange with the shape degree of freedom essentially kept frozen. (2) The dinuclear molecular states can decay only into dinuclear channels or stay trapped until the nuclei fuse. (3) The actual numerical solution of the coupled transport equations that describe the evolution of the dinuclear complex is done in the equilibrium limit. There is evidence[11,8] that the first assumption is not universal. Assumption #2 is approximately correct; if we consider other processes such as nucleon emission from one of the excited "partners" in the dinuclear complex, the remaining complex will be "cold" enough to fuse. Data on orbiting of $^{28}Si + ^{14}N$ (Ref. 8) provide the justification for choosing the equilibrium solution to the transport equations.

RESULTS

What the model calculates are probabilities $P_\ell(N,Z)$ for fragmentation of the flux trapped in the dinuclear complex into a channel with two nuclei one of which has N neutrons and Z protons and the other its complement. In the equilibrium limit the probabilities $P_\ell(N,Z)$ are given by the expression (Ref.7)

$$P_\ell\ (N\ Z) = \frac{\rho_\ell(N,Z,R_R)}{\sum_{NZ}'[\rho_\ell(N,Z,R_M) + \rho_\ell(N,Z,R_B)]}$$

where $\rho_\ell(N,Z,R_B)$ and $\rho_\ell(N,Z,R_M)$ are the level densities of the dinuclear complex at the top of the potential barrier $R = R_B$ and at the potential minimum $R = R_M$, respectively (see for example Fig. 4). These probabilities are then used to calculate observables such as the kinetic energies of the fragments emitted from the dinuclear complex, the absolute cross section for orbiting products with specific mass and charge and finally the absolute fusion cross section.

In principle it should be possible to fit all the data by changing the parameters of the nucleus-nucleus potential and the level density expression. The parameter changes are constrained, though, because changes in them affect two observables. A change in nuclear potential parameters will directly affect the kinetic energy values derived and the cross section for fusion and changes in level densities will affect the orbiting and fusion cross sections. For the data shown in Figs. 7, 8, and 9 actually no parameter variation was made. The nuclear potential chosen was the proximity potential from Ref. 3 (with only slight changes allowed by the quoted uncertainties) and a Fermi gas expression with the level density parameter a = A/8 was used.[15] The results of this first attempt are very encouraging. We are now in the process of refining our calculation. The crude approximations used in our phase space (level density) calculations will be remedied, and the constraint of nuclear sticking will be imposed also on the phase space calculations. While we expect some quantitative variations we do not expect any qualitative change in these results.

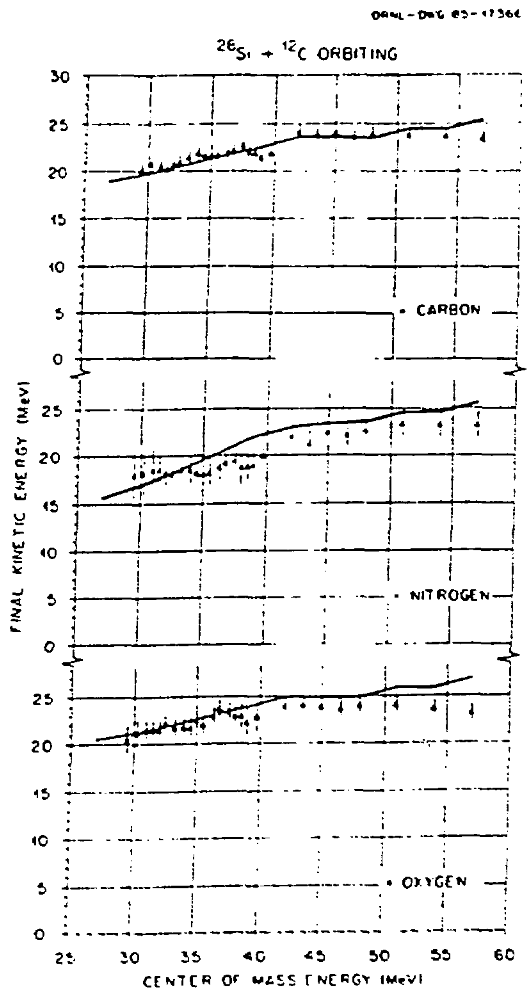

Fig. 7

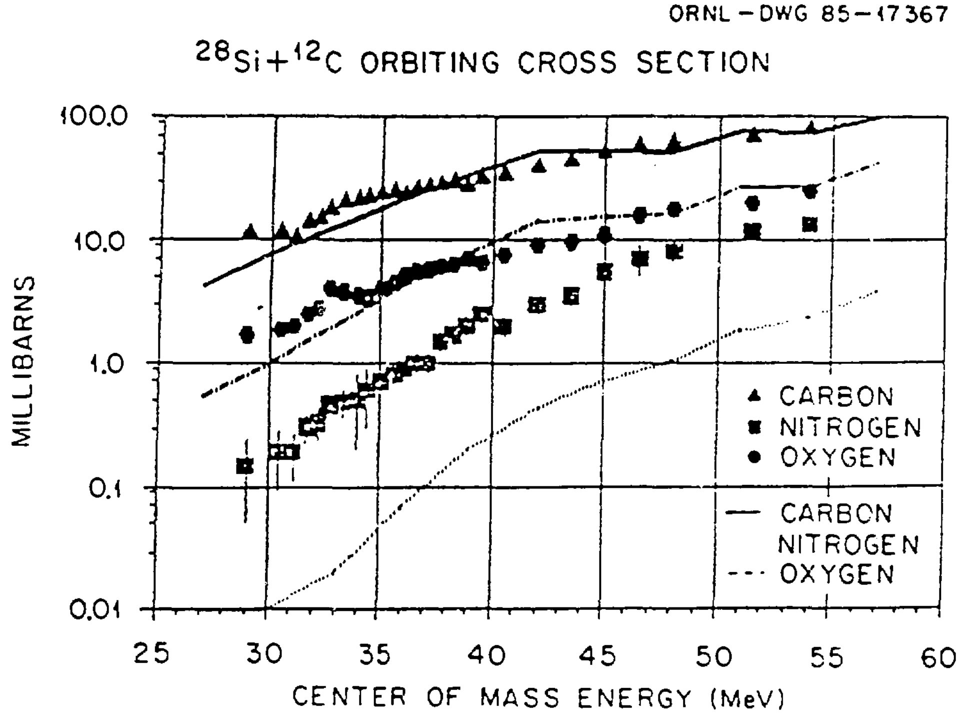
ORNL-DWG 85-17367
$^{28}Si+^{12}C$ ORBITING CROSS SECTION
100.0
10.0
1.0
0.1
0.01
MILLIBARNS
25
30
35
40
45
50
55
60
CENTER OF MASS ENERGY (MeV)
▲ CARBON
■ NITROGEN
● OXYGEN
— CARBON
NITROGEN
--- OXYGEN

Fig. 8

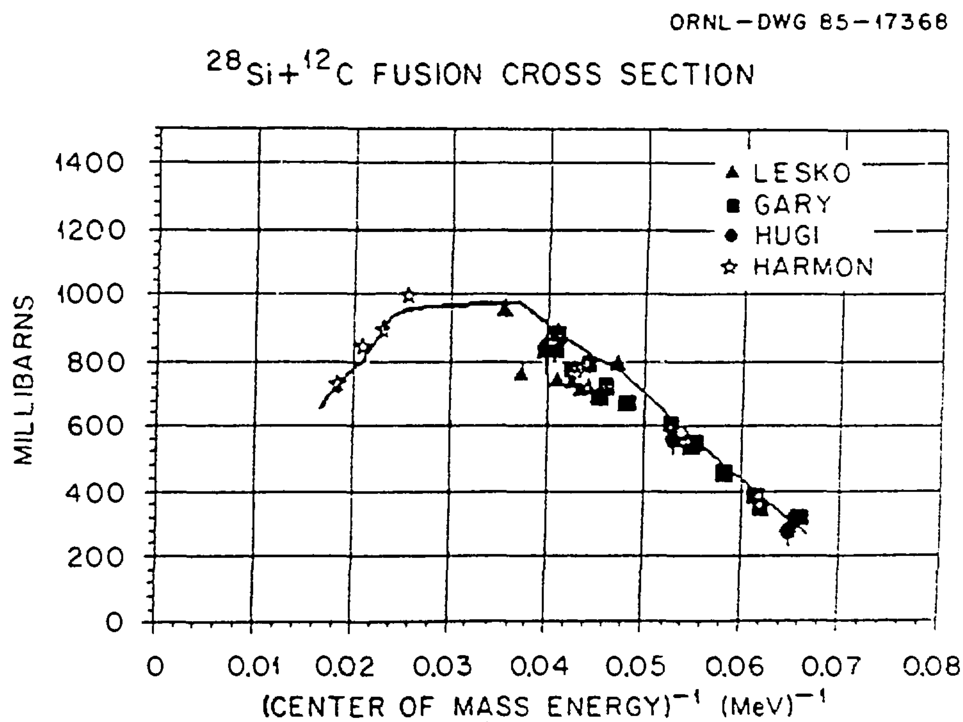
ORNL-DWG 85-17368
$^{28}Si+^{12}C$ FUSION CROSS SECTION
1400
1200
1000
800
600
400
200
0
MILLIBARNS
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
(CENTER OF MASS ENERGY)$^{-1}$ (MeV)$^{-1}$
▲ LESKO
■ GARY
● HUGI
☆ HARMON

Fig. 9

*Operated by Martin Marietta Energy Systems, Inc. under contract DE-AC05-84OR21400 with the U.S. Department of Energy.

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