Complex Fragment Emission for the Study of the Fermi Energy Domain Nuclear Collisions*

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Complex fragment production in the Fermi energy domain heavy ion collisions is studied. The physics used for the description of the various remnants produced in the entrance channel is based on fireball model taking into account the kinematic and dynamic features of the collision partners, and the decay processes are simulated by a version of the statistical binary decay model. Applications are shown to the target-like products for reactions of copper with 24.0, 31.1, 38.5 and 46.4 MeV/u ^{12}C. Absolute comparisons with experimental data give a very well overall agreement.

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It is interesting to study where the complex fragment (CF), $Z > 2$, comes from. CF emission in intermediate energy nuclear reactions has been a subject of both experimental and theoretical interest for many years.[1] The process of CF emission from excited compound nuclei has been systematically studied for reactions (X+Be, C, Al) from 8 MeV/u up to 100 MeV/u (Ref. 2–5). Based on such well-established knowledge, we consider first statistical sequential emission from equilibrated primary sources formed in complete and incomplete fusion process and applied successfully to reproduce the mass yield distribution of the target residues in the reaction of 42 MeV/u $^{12}C+^{115}In$ measured by radiochemical work,[6] however, the fraction of the total reaction cross section for each fusion process was regarded as an adjustable parameter. To withdraw this assumption, in present paper we show first that a careful analysis of the entrance-channel dynamics on the basis of fireball model[7] coupled to a complete description of sequential binary decay channels can account for most of the CF products of the target residues in the Fermi energy domain heavy ion collisions.

The statistical decay calculations were performed using the Monte Carlo code GEMINI.[4]

Calculating the mass distributions requires the summation of the entrance channel l-wave as follows:

$$\sigma(A) = \sum_{l=0}^{l_{max}} (2l+1) T_l(A) \,, \tag{1}$$

where $T_l(A)$ are the probabilities of the given decays proceeding at angular momentum l. The statistical calculations have been summed to l_{max} that provides the best fit to the experimental data. Good agreement with the shapes of the experimental cross sections has been obtained using values of l_{max} predicted by the Bass models.[8] Considering the binary decay of complete fusion compound nuclei gets the results shown in Fig. 1 as the histograms, solid circles are experimental data taken from Ref. 9. Parts of the CF which are larger than projectile and lower than target are explained very well by GEMINI code. This may indicate that the complex fragments are produced in highly equilibrated "binary" processes. The failed predictions of the

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cross sections for mass number around target may be attributed to the onset of the incomplete fusion process above 20 MeV/u (Ref. 3).

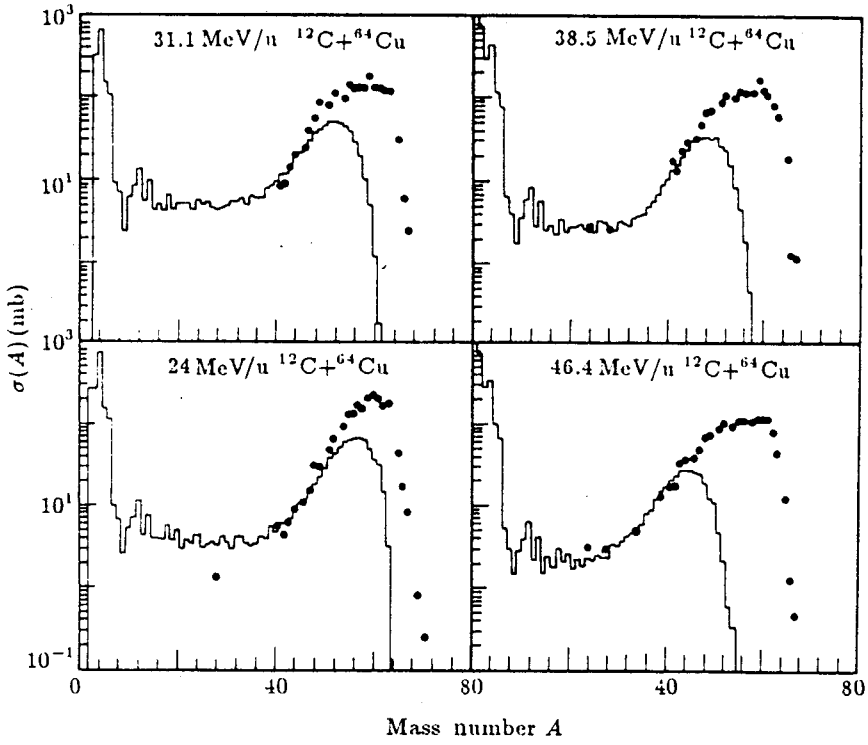

Fig. 1. Inclusive mass yield distributions for the reaction $^{12}C+^{64}Cu$ at 24.0, 31.1, 38.5 and 46.4 MeV/u. Solid circles are radiochemical experimental data from Ref. 9 ; histograms represent the calculations of GEMINI code based solely on assumption of the occurrence of complete fusion.

As bombarding energy increases, incomplete fusion sets in. There are two problems to apply GEMINI code. One is whether the triangular l-wave distribution used for complete fusion can still represent the spin distribution of the incomplete fusion, the other is that the theoretical cross sections are very dependent on the values of l_{max} and there are no reliable models from which this quantity can be got. A simple prescription to estimate the mass transfer, momentum transfer, and excitation energy of the incomplete fusion product is taken using the fireball model[7] in this work, in which the number of nucleons from the projectile being possibly trapped in the target is obtained in the pure geometrical limit corresponding to a straight trajectory for the incoming projectile at a given impact parameter and the question of linear-momentum transfer in Fermi energy domain demands an elucidation of the essential kinematic and dynamic features of the associated interactions which is considered by Moretto's proposals.[10] For target A picking up β from projectile B forming compound-like nucleus $A+\beta$, the momentum transfer is as follows:

$$\frac{P_{A+\beta}}{P_0} = \frac{\beta}{B}\left[1+\frac{A(B-\beta)}{\beta(A+B)}\left(1-\sqrt{1-\frac{2\Delta\beta}{m_\beta v_0^2}}\right)\right],$$

$$m_\beta = \frac{(A+\beta)(B-\beta)}{A+B}, \quad v_0 = \frac{AP_0}{B(A+\beta)}. \tag{2}$$

Here P_0 is the initial momentum, $P_{A+\beta}$ is the momentum of $A+\beta$ and $\Delta\beta$ is the separation energy. So the excitation energy of nucleus $A+\beta$ is

$$E^* = E^{\rm CM}_{A+\beta} + Q_{\rm CN} ,$$

$$E^{\rm CM}_{A+\beta} = E_0\left(1 - \frac{Bf^2}{A+\beta} - \frac{B(1-f)^2}{B-\beta}\right) , \quad f = \frac{P_{A+\beta}}{P_0} , \tag{3}$$

where $E^{\rm CM}_{A+\beta}$ is the energy of $A+\beta$ in central-of-mass system and $Q_{\rm CN}$ is its reaction Q value.

And another assumption is to retain the triangular shape of the spin distribution. For incomplete fusion Eq. (1) is replaced by:

$$\sigma(A) = \sum_i \sum_{l=l_{\rm min}}^{l_{\rm max}} (2l+1)T_l(A) , \tag{4}$$

where i is incomplete fusion channel which varies from 1 to 12 representing neutron or proton transfer to complete fusion in this system. Incomplete fusion occurs assuming ^{12}C sheared into two parts by target at certain impact parameter and ^{64}Cu picks up one part of projectile. According to our approach, Table 1 lists all the properties of the incomplete fusion compound nuclei present at the entrance channels for 24.0 MeV/u ^{12}C+^{64}Cu. From the table, the total cross section and average excitation energy are found to be 2190.7 mb ($\sum \sigma_i$) and 136.3 MeV ($\sum E_i P_i$) which agree well with experimental values 2205.7 mb and 135.0 MeV (Ref. 9) respectively.

Table 1. Charge, mass, excitation energy, angular momentum, cross section and probability of each fusion channel at different impact parameters.

b (fm)	Z	A	$l_{\rm min}$ ($\hbar$)	$l_{\rm max}$ ($\hbar$)	Exc. energy (E_i) (MeV)	Cross section (σ_i) (mb)	Probability (P_i)
2.053	35	76	0	22	247.4	141.93	9.99%
2.622	34	75	20	26	240.7	102.30	6.31%
3.072	34	74	24	28	226.4	97.66	6.08%
3.459	33	73	25	29	206.3	121.02	6.01%
3.817	33	72	26	29	178.4	121.36	6.16%
4.158	32	71	25	28	170.8	148.63	6.46%
4.494	32	70	24	26	150.9	139.29	6.89%
4.831	31	69	22	23	126.6	117.19	7.47%
5.180	31	68	19	20	94.4	154.64	8.28%
5.552	30	67	15	17	86.2	330.28	9.45%
5.968	30	66	11	12	63.16	349.64	11.37%
6.494	29	65	6	6	33.54	367.38	15.53%

The histograms in Fig. 2 show the results of statistical decay calculations in above descriptions. Except a few large products which are due to quasielastic scattering and deeply inelastic scattering can not be considered, all the fragments are reproduced excellently at different bombarding energies. The good agreement between the model calculations and the experimental data in the ^{12}C+^{64}Cu system from 24.0−46.4 MeV/u is very strong evidence for non-equilibrium processes and compound nucleus formation in this energy region.

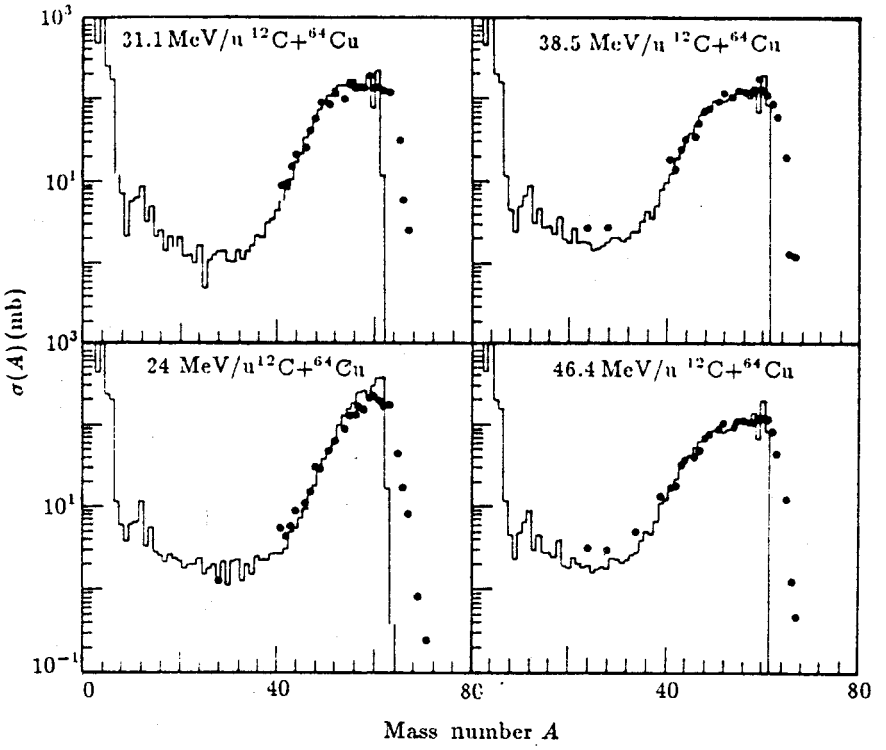

Fig. 2. Same as Fig. 1, the calculated results are from complete and various incomplete fusion processes coupled to GEMINI cascade (see text).

In summary, a refined statistical model calculation is proposed to study the mechanisms of complex fragment produced in intermediate energy nuclear collisions. As examples of the first applications, the mass distributions measured in the reaction of 24.0 – 46.4 MeV/u ^{12}C with ^{64}Cu is examined. The excellent agreement between theoretical estimations and experiments shows the common origin of all the complex fragments and indicates the important role of compound nuclei in intermediate energy heavy ion reactions.

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