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Competition Between Fragmentation and Transfer in 46.7 MeV/u ^{12}C Induced Reactions

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The coexistence and competition between fragmentation and transfer in the 46.7 MeV/u ^{12}C induced reactions have been discussed. The reduced longitudinal momentum distribution width for the transfer reaction, extracted from our experiment, is 44 ± 10 MeV/*c*, which is smaller than that for the fragmentation (80 ± 10 MeV/*c*). The probabilities for both the projectile fragmentation and the transfer processes are observed to be dependent on the structure of the transferred cluster.

1. INTRODUCTION

The heavy ion induced nuclear reactions at intermediate energies are expected to be characterized by both the mean field effect in the low energy region and the nucleon-nucleon collision at high energies. The nucleus-nucleus interaction time in heavy ion collision becomes comparable to or even shorter than the relaxation time of the intrinsic degree of freedom in the nucleus, and the nonequilibrium phenomena become more and more important in this energy region. The intermediate energy region is a transitional region from one-body dissipation to two-body dissipation, the mean field effect is expected to give way progressively to the nucleon-nucleon collision, with the increase of the incident energy.

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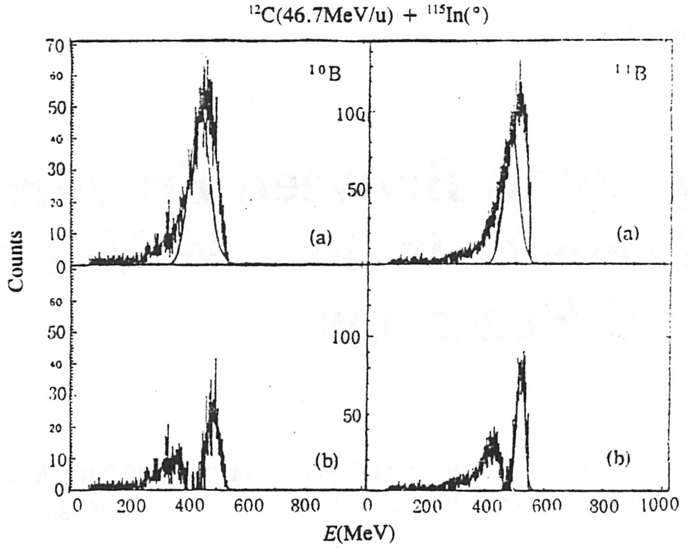

Fig. 1
The separation of the contributions from the projectile fragmentation and the transfer reaction.

It was found that the transfer reaction still contributes to the energy spectra of the heavy ion reaction products in experiments in the intermediate energy region [1], and fragments slightly heavier than the projectile were observed in these experiments. Three constituents, 1) high energy component from quasi-elastic or transfer processes, 2) low energy component from dissipative processes and 3) intermediate energy fragmentation peak in between, can be clearly observed in the energy spectra of the projectile-like fragments (PLF) slightly lighter than the projectile. These indicate that both the projectile fragmentation and the transfer process contribute to the formation of the PLF.

The coexistence of the fragmentation and the transfer was proved in many experiments in the intermediate energy region [2,3]. Compared to the fragmentation, the probability of the transfer reaction decreases rapidly with the increase of the incident energy. In the low energy heavy ion reactions, the phase space limitation restricts the quasielastic transfer to the bound states of the projectile or target nucleus. As the incident energy increases, the overlap between the projectile and target nucleus momentum distributions will decrease, and the transfer to the unbound states of the projectile or target nucleus can be expected. The contributions of the transfer reaction to the PLF can be determined in the coincident experiment [4]. The experiment showed, that the transfer reaction mainly contributes to the fragments, close to the projectile. The quasielastic energy spectra of the few nucleon transfer to the continuous states can be explained by DWBA calculation combined with the energy level density [5].

To investigate the projectile fragmentation and the transfer reaction, an experiment has been performed at HIRFL accelerator. In the experiment 46.7 MeV/u ^{12}C beam was used to bombard different target nuclei. A telescope composed of a CsI(Tl) scintillator and a set of semiconductor detector was used to detect the emitted products in the angular region of 5°-20° [6].

2. SEPARATION OF THE FRAGMENTATION AND TRANSFER CONTRIBUTIONS TO PLF ENERGY SPECTRA

In the laboratory system, the energy spectra of the products from the projectile fragmentation can

Table 1
Momentum distribution width corresponding to transfer reaction.

^{13}C, E/A = 46.7 MeV Momentum distribution width corresponding to transfer								
PLFs	σ(MeV/c)				σ_0(MeV/c)			
Target	^{10}B	^{11}B	^{10}C	^{11}C	^{10}B	^{11}B	^{10}C	^{11}C
^{58}Ni	61.1	46.5	60.3	47.9	45.3	46.5	44.7	47.9
^{64}Ni	67.4	53.4	66.2	51.4	50.0	53.4	49.1	51.4
^{115}In	54.6	42.1	46.7	35.9	40.5	42.1	34.6	35.9
^{197}Au	57.5	41.1	49.7	35.4	42.6	41.1	36.9	35.4

be obtained under the assumption of a Gaussian distribution of the product momenta in the projectile frame. When the mass of the fragment A_F is much smaller than that of the projectile, the higher energy component of the energy spectrum is attributed mainly to the projectile fragmentation, and the contribution of the transfer process is negligible. By fitting the experimental energy spectra, the most probable energies $\bar{E}$ of ^6Li, ^7Li, ^7Be and ^9Be for the fragmentation part were extracted for each reaction system [6]. For a fragment with mass A_F close to the projectile, such as ^{10}B, ^{11}B, ^{10}C and ^{11}C, the transfer also contributes to their formation and the high energy component of the energy spectra is a superposition of the projectile fragmentation and the transfer reaction contributions, so the position of the experimental energy peak is higher than that expected from pure fragmentation. The contribution of the fragmentation was obtained in the following way [7].

(1) The reduced longitudinal momentum distribution width σ_0 extracted from PLF of ^6Li, ^7Li, ^7Be and ^9Be is 80 $\pm$ 10 MeV/c, independent of the mass of the PLF. In fitting the energy spectra of heavier PLF, the same value of σ_0 was also used.

(2) In different reaction systems, the most probable energies $\bar{E}$ of the fragmentation part for the heavier fragments were obtained by extrapolating the values for the lighter fragments.

(3) The lower side of the higher energy component of the experimentally measured fragment energy spectrum was fitted.

According to the above procedure, the higher energy component in the ^{10}B, ^{11}B, ^{10}C, ^{11}C PLF's energy spectra can be separated into the fragmentation and the transfer parts. After subtraction of the fragmentation contribution, the residue spectra were supposed to be coming from the transfer and dissipative processes as shown in Fig. 1. In this way, the contributions from different reaction mechanisms were roughly separated, and their dependence on the reaction mechanisms could be studied. Here the particle evaporation of the primary fragments has not been corrected, so this is only a qualitative discussion.

3. FRAGMENTATION AND TRANSFER LONGITUDINAL MOMENTUM DISTRIBUTION WIDTHS

Based on the independent particle statistic model, Goldhaber proposed that the momentum distribution width σ depends on the fragment mass A_F in the following way [8],

$$\sigma^2 = \sigma_0^2 \frac{A_F(A_P - A_F)}{A_P - 1}. \qquad (1)$$

where σ_0 is the reduced momentum distribution width which is determined by Fermi motion and does not depend on the fragment mass. The reduced longitudinal momentum distribution width σ_0, extracted

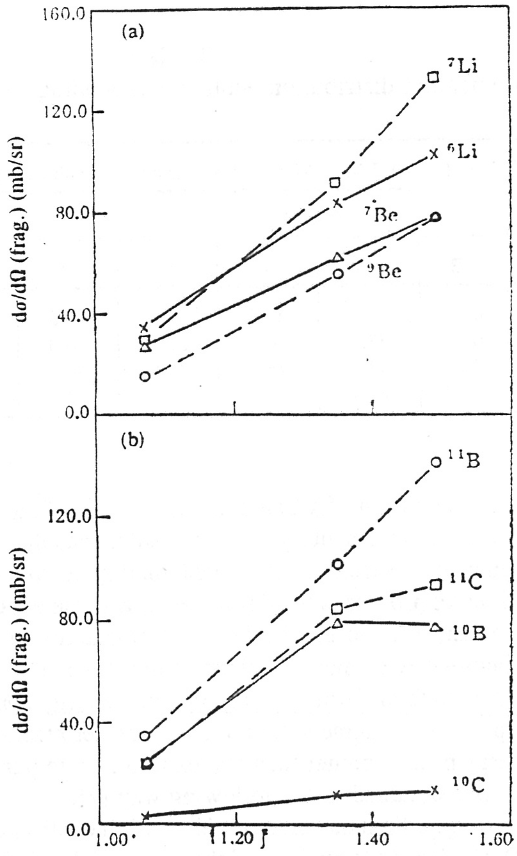

Fig. 2

(a) The projectile fragmentation cross section for PLF of ^{6}Li, ^{7}Li, ^{7}Be and ^{9}Be at 5°. (b) The projectile fragmentation cross section for PLF of ^{10}C, ^{11}C, ^{10}B and ^{11}B at 5°.

from the 46.6 MeV/u ^{12}C induced reactions, is 80 ± 10 MeV/*c* [6]. This means that the momentum spectra of the projectile fragmentation products can be explained by using the momentum sphere model under Goldhaber's assumption [9].

When the masses of PLF are close to the projectile mass, the high energy component of the PLF energy spectra is a superposition of the contributions from the projectile fragmentation and transfer reaction, and the average energy of the transfer contribution should be slightly higher than that of the fragmentation contribution. After subtraction of the fragmentation part from the PLF's energy spectrum according to the procedure mentioned above, and the residual energy spectrum was transformed into invariant velocity spectrum, the longitudinal momentum distribution width can be extracted from the higher velocity component of the residual velocity spectrum by a Gaussian fit. The reduced momentum distribution width for the transfer reaction was calculated by using Eq. (1). The results for different reaction system are listed in Table 1. The obtained reduced momentum distribution width for the transfer is 40 ± 10 MeV/*c*, consistent with the data from other experiments at similar incident energies [9]. The momentum distribution width for the transfer is narrow compared to that for the fragmentation. In the transfer reaction the nucleon is transferred to a definite final state under the constraint of the momentum conservation. In this case, the limitation in the phase space is more rigorous, but this is not the case in the projectile fragmentation [10].

Table 2
The fragmentation probability ratios for ^{7}Li and ^{7}Be formed in ^{12}C induced reactions at 5°.

Target	^{58}Ni	^{115}In	^{197}Au
$(N/Z)_{target}$	1.07	1.35	1.49
$(d\sigma/d\Omega)_{frag}(^{7}Li/^{7}Be)$	1.08	1.47	1.70

Table 3
The transfer cross section ratio of the fragments in ^{12}C induced reactions at 5°.

Target	^{58}Ni	^{115}In	^{197}Au
$(N/Z)_{target}$	1.07	1.35	1.49
$(d\sigma/d\Omega)_{trans.}(^{10}C/^{10}B)$	0.25	1.02	1.12
$(d\sigma/d\Omega)_{trans.}(^{11}C/^{11}B)$	1.44	1.52	1.84

4. COMPETITION BETWEEN PROJECTILE FRAGMENTATION AND TRANSFER REACTION

The heavy ion induced nuclear reaction in the intermediate energy region is complicated due to the coexistence and competition of different reaction mechanisms. Both the projectile fragmentation and the transfer reaction contribute to the higher energy part of the PLF's energy spectra. With the increase of the incident energy from the low energy to the intermediate energy, the fragmentation plays a more and more important role, and the probability of the transfer reaction becomes smaller and smaller.

The existence of the transfer reaction has been proved in the 46.7 MeV/u ^{12}C induced reaction. The nuclides heavier than the projectile ^{12}C such as ^{13}C, ^{12}N, ^{13}N and ^{14}N were observed in the experiment at smaller angles, and their energy spectra are mainly contributed to the higher energy part. These facts can result only from the transfer reaction. So when the PLF's mass is close to and smaller than the projectile mass, both the projectile fragmentation and transfer contribute to the PLF's energy spectra, but their contributions can be separated by the procedure mentioned above. After subtraction of the fragmentation contribution from the PLF's energy spectrum, the higher energy component of the residual energy spectrum is considered to be the contribution from the transfer reaction.

The fragmentation cross sections of various fragments from different reaction systems investigated are shown in Fig. 2(a) and (b). For each kind of fragments the experimental results show that the fragmentation cross section increases with the increasing of the geometrical size of the target nucleus, consistent with the abrasion model prediction. The fragmentation probability is concerned with the structure of the abraded cluster. The cross section of ^{7}Li fragment is larger than that of ^{7}Be in all reaction system studied. In the case of ^{7}Li fragment, there are three protons and two neutrons in the abraded ^{5}Li cluster. In the case of ^{7}Be fragment, there are two protons and three neutrons in the abraded ^{5}He cluster. Different structure of the abraded clusters leads to different fragmentation probabilities. The similar situation is for ^{10}C and ^{10}B fragments, and the cross section of ^{10}B fragment is much larger than that of ^{10}C. In the case of ^{10}B one proton and one neutron are abraded, and in the

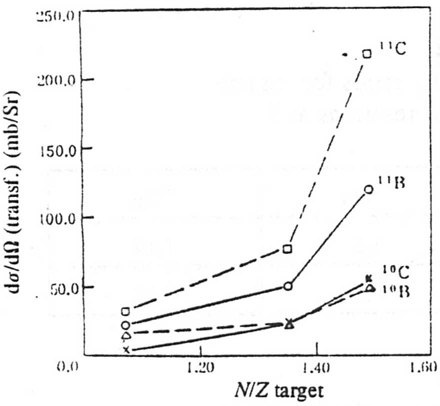

Fig. 3
The transfer cross section for PLF of ^{10}C, ^{11}C, ^{10}B and ^{11}B at 5°.

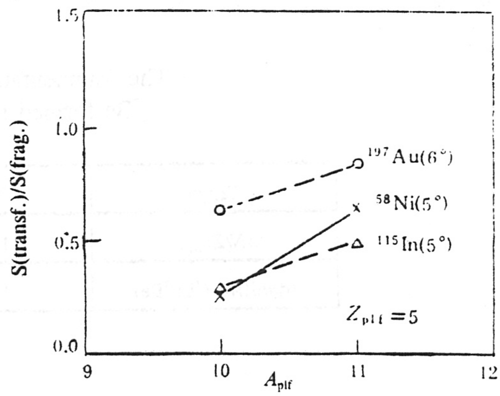

Fig. 4
The transfer to fragmentation cross section ratio for PLF of ^{10}B and ^{11}B as a function of the fragment mass at 5°.

case of ^{10}C, two neutrons are abraded. Two neutrons can not form a stable bound state, so the probability of the formation of a $2n$ cluster is rather low. This leads to the lower cross section of ^{10}C fragments. At the same time, the fragmentation probability also shows some dependence on the structure of the target nucleus. The cross section ratios of ^{7}Li and ^{7}Be fragments in different reaction systems are shown in Table 2, from which one may find that the cross section ratios increase with increasing N/Z ratio of the target nucleus. The target nucleus with larger N/Z ratio tends to abrade the cluster with rich protons. This can also explain why the cross section of ^{11}B is larger than that of ^{11}C in the experiment.

The following is the discussion about the transfer reaction cross section in various reaction systems. Figure 3 shows that the transfer cross section of ^{11}C and ^{11}B fragments is obviously larger than that of ^{10}C and ^{10}B fragments. This indicates that the probability of one nucleon transfer is much larger than the probability of two nucleon transfer. The transfer probability also increase with the geometrical size of the nucleus. The transfer cross section is clearly dependent on the structure of the target nucleus. For instance, in the case of ^{58}Ni target, the transfer cross section of ^{10}B is larger than that of ^{10}C. This can be interpreted by smaller N/Z ratio of ^{58}Ni target nucleus, to which it is easier to transfer neutrons rather than protons. From Table 3 one may find that the transfer cross section ratios of ^{10}C and ^{10}B increase with the N/Z ratio of the target nucleus. This can also explain why the transfer cross section ratios of ^{11}C and ^{11}B increase with the N/Z ratio of the target nucleus.

It was found in the experiment, that the transfer cross sections of ^{11}C, ^{11}B, ^{10}C and ^{10}B are larger than that of ^{13}C and N isotopes for all investigated reaction systems. This indicates that the transfer prefers to occur from lighter nucleus to the heavier ones. Besides the contribution of the transfer to continuous states, the contribution of the transfer to the separated states was also observed in the energy spectra of ^{11}C and ^{11}B fragments. This result needs to be analyzed further.

Due to the coexistence of projectile fragmentation and the transfer reaction mechanisms, it is important to investigate the competition between them. Figure 4 shows the ratios of the transfer reaction cross section to the fragmentation cross section for ^{10}B and ^{11}B from three reaction systems. The fewer nucleons are transferred, the larger transfer to fragmentation ratio will be. The transfer reaction mainly contributes to the fragments close to the projectile. When the fragment mass is much smaller than the projectile mass, the projectile fragmentation becomes the main source of the PLF, and the contribution of the transfer reaction can be neglected.

The relation between the transfer to fragmentation ratios and the target nuclei is shown in Fig. 5. The ratio value increase with the N/Z value of the target nucleus. For ^{10}B and ^{11}B, this ratio increase

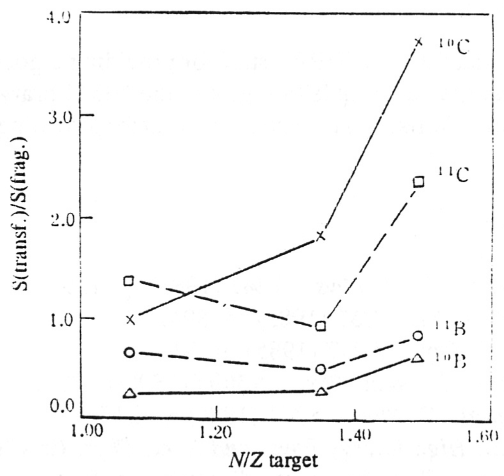

Fig. 5
The transfer to fragmentation cross section ratio for PLF of ^{10}C, ^{11}C, ^{10}B and ^{11}B at 5° in different reaction systems.

moderately, and for ^{10}C and ^{11}C it increases rapidly. This means that the heavier the target nucleus is, the easier the transfer is to occur. The different behavior of the transfer to fragmentation ratio depending on the target nucleus for B and C isotopes reflects the nuclear structure effect on the reaction mechanism. The relative contributions of the transfer reaction and the fragmentation are affected by the *N/Z* ratio of the target nucleus, depending on the structure of the transferred cluster.

5. CONCLUSIONS

An experiment with 46.7 MeV/u ^{12}C beam bombarding on the ^{58}Ni, ^{64}Ni, ^{115}In and ^{197}Au targets was performed at the HIRFL heavy ion accelerator in Lanzhou. The reaction products emitted in the angular region of 5°-20° were measured with a telescope consisting of transmission silicon detectors and a CsI(Tl) scintillator. The projectile fragmentation and transfer reaction and the competition between them in the ^{12}C induced intermediate energy heavy ion reactions were investigated.

The higher energy component of the PLF's spectra is mainly attributed to the projectile fragmentation. When the mass of the fragment is close to the projectile mass, the transfer reaction also contributes to the formation of the PLF. For the PLF close to the projectile, under the assumption of a Gaussian distribution of the momentum in the projectile frame, the energy spectrum of the fragmentation part can be fitted, by using the most probable energies obtained by extrapolating method and the average reduced longitudinal momentum distribution width extracted from the experiment, and then the contributions from the projectile fragmentation and the transfer reaction were separated. The separation can also be made experimentally by a coincident measurement between the light particles and PLF. This kind of experiment now is under consideration.

The average reduced longitudinal momentum distribution width, extracted from the part contributed by the transfer reaction, is 44 $\pm$ 10 MeV/c, less than the value of 80 $\pm$ 10 MeV/c for the projectile fragmentation part. This means that the transfer reaction is more restricted in the phase space. The probabilities of the projectile fragmentation and the transfer reaction depend on the structure of abraded or transferred cluster and increase with the mass of the target nucleus. The transfer of the nucleons is mainly from the lighter partner to the heavy one. The transfer reaction mainly contributes to the formation of the PLF close to the projectile. When the mass of the PLF is much less than that of the projectile, the major contribution is from the projectile fragmentation.

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REFERENCES

[1] M. C. Mermaz *et al.*, *Nucl. Phys.*, **A441** (1985), p. 129.
[2] S. Wald *et al.*, *Phys. Rev.*, **C32** (1985), p. 894.
[3] D. Guerreau, *Nucl. Phys.*, **A447** (1985), p. 37c.
[4] J. C. Steckmeyer *et al.*, *Nucl. Phys.*, **A500** (1989), p. 372.
[5] M. C. Mermaz *et al.*, *Z. Phys.*, **A342** (1986), p. 217.
[6] Lu Guanhua *et al.*, *High Energy Phys. and Nucl. Phys.* (in Chinese), 17(1993)166.
[7] K. Van Bibber *et al.*, *Phys. Rev. Lett.*, **43** (1979), p. 840.
[8] A. S. Goldhaber, *Phys. Lett.*, **53B** (1974), p. 306.
[9] Zhu Yongtai *et al.*, *High Energy Phys. and Nucl. Phys.*, **14** (1990), p. 195.
[10] K. W. MeVoy and M. C. Nemes, *Z. Phys.*, **A295** (1980), p. 177.