High Energy Physics and Nuclear Physics

Volume 16, Number 1

A Study on the Correlation Between Projectile-Like Fragments and α-Particles in ^{20}Ne(14.7, 19.2 MeV/u) + ^{58}Ni Reactions

Hu Xiaoqing, Zhu Yongtai, Shen Wenqing, Li Songlin,
Zhan Wenlong, Xi Hongfei, Zhu Xiang and Zhang Zhen

Institute of Modern Physics, the Chinese Academy of Sciences, Lanzhou, Gansu, China

The coincidence between projectile-like fragments and α-particles emitted from ^{20}Ne (14.7 MeV/u, 19.2 MeV/u) + ^{58}Ni reactions has been studied. The coincident events were caused by the sequential decay of the excited primary fragments and by the "uncorrelated" coincidence between forward emitted α-particles and projectile-like fragments, which formed in a deeply dissipated reaction process. This reaction process means that the α-particle flied off the ^{20}Ne projectile in the initial stage of the reaction and then the residual ^{16}O collided with the target nucleus dissipatively. We call it "incomplete deep inelastic process".

1. INTRODUCTION

The coincidence between projectile-like fragments and light particles has often been measured in heavy ion reactions. These projectile-like fragments and light particles come from primary projectile-like products. This process is called projectile fragmentation [1]. In the high energy case, the projectile fragmentation can be interpreted in the framework of "participant-spectator" model [2]. In the peripheral collision, the light particles are emitted from the contact region of the projectile and target nuclei, and the main part of the projectile flies away with a velocity close to the beam velocity. The momentum distribution of the spectator is characterized by the Fermi motion inside the projectile [3]. In the low energy case, peripheral interaction leads to transfer reaction, inelastic and deep inelastic collisions. The excited reaction products decay sequentially with the emission of light particles. So the correlation between projectile-like fragments and light particles also can be

Supported by the National Natural Science Foundation of China.
Received on January 21, 1991.

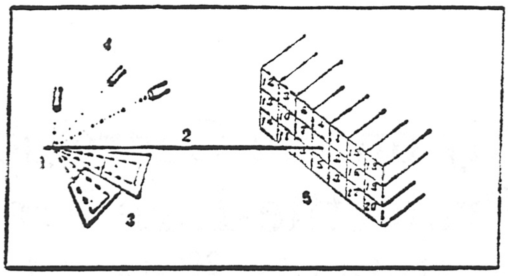

Fig.1

The layout of the experimental setup.

(1) Target; (2) Beam; (3) Position sensitive ionization chamber telescopes; (4) Silicon detector telescopes; (5) Plastic scintillator detector array.

observed. But the reaction process is mainly governed by the mean field effect, which is different from the nucleon-nucleon interaction in the high energy case.

In the intermediate energy domain (10 MeV/u—100 MeV/u), the heavy ion interactions are characterized by both the mean field effect as in low energy case and the nucleon-nucleon interaction as in the high energy case [4,5,6,7]. The reaction process becomes more complicated. The study on the peripheral heavy ion reaction in intermediate energy domain provides useful information about the reaction characteristics. At the lower energy side of intermediate energy region, the projectile fragmentation differs from that in the high energy case, and some low energy characters are expected to be present. Based on this consideration, the projectile fragmentation in the peripheral reaction of 14.7 MeV/u and 19.2 MeV/u ^{20}Ne on ^{58}Ni target was studied. A detector array is put in the forward direction detecting the light particles emitted from the reaction, and the projectile-like products are detected at different angles. By analyzing the correlation between these two kinds of products, the features of peripheral reaction at these energies can be studied.

In the next section the experimental setup will be described. The existence of sequential decay based on the energy correlation of two products is discussed in section 3. In section 4 a Monte Carlo simulation and angular correlation will be presented, showing the existence of a incomplete reaction process.

2. EXPERIMENTAL SETUP

The ^{20}Ne beam of 294 MeV and 384 MeV energies provided by KVI cyclotron bombarded the 1.5 mg/cm^2 ^{58}Ni target. The detected reaction products were light charged particles in the forward direction (including isotopes of H and He) and projectile-like fragments at different angles. The experimental setup is shown in Fig.1. An array of 20 plastic scintillator phoswich detectors [8] were placed on the forward direction. Each of them consists of a 1-mm-thick fast scintillator (NE102A) and a 15-mm-thick slow scintillator (NE115). Each has an effective area of 65×65 mm^2. The covered angular region is from $-20°$ to $+20°$ in plane and from $-10°$ to $+10°$ out of plane. The central element was moved away for passing through of the beam. The total solid angle was about 0.2 sr. The different isotopes of H and He were clearly identified. The energy calibration was performed by using α-beam of various energies. Nearly linear light response to energy of H and He isotopes was obtained.

Three sets of semiconductor detector telescopes were mounted at different angles on the other side of the beam to detect the projectile-like fragments. Their thickness was 50 μm + 5000 μm, 20

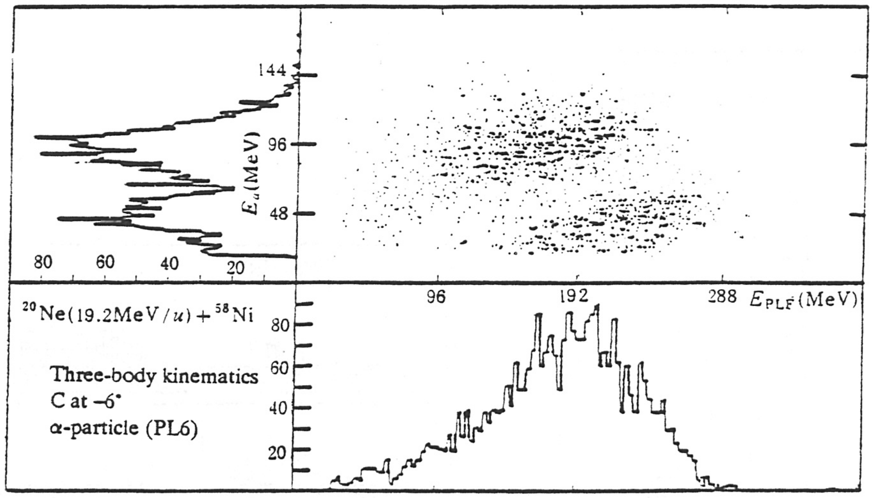

Fig.2
The energy correlation between carbon (at −6°) and α-particles detected by neighboring PL6 detector and corresponding energy spectra.

μm + 3000 μm and 15 μm + 2000 μm, respectively. The element identification of these telescopes for the projectile-like fragments is perfect. The experimental data were written on the tape event by event and off-line analysis was performed at a VAX8350 computer in the Institute of Modern Physics.

3. RESULTS AND DISCUSSION

According to the impact parameter b, heavy ion reactions can be divided into peripheral and central collisions. At low energies peripheral collision leads to inelastic or deep-inelastic collisions. Projectile-like products are excited. These excited primary products decayed subsequently via the emission of light particles (the so-called sequential decay). The coincident events between secondary projectile-like fragment and light particle were observed in the experiment. Do all coincident events between secondary projectile-like fragment and light particle come from the sequential decay at higher energies (15—20 MeV/u)?

The energy and angular correlations between projectile-like fragments and α-particles were studied in the ^{20}Ne + ^{58}Ni reactions. The energy correlation between the projectile-like fragment carbon detected at 6° and an α-particle detected by neighboring plastic scintillator detector is shown in Fig.2. It is clearly seen from the scatter plot that there are two components corresponding to the two peaks in the energy spectrum of α-particles.

Known from the three-body kinematics analysis, the primary reaction product decays when its excitation energy exceeds the ground state binding energy of the available decay channel. The relative kinetic energy between the two secondary decay products in the primary ejectile system is equal to the difference between the excitation energy and ground state binding energy (assuming both secondary products are in ground state). Due to the geometric and kinematic effects, the energy spectra of these two secondary products will have two components corresponding to the forward and backward emission of α-particles in the system of primary ejectiles, as shown in the figure.

Fig. 2 shows the correlation events between the projectile-like fragment and α-particle, which mainly come from the sequential decay of the excited primary projectile-like products. The energy

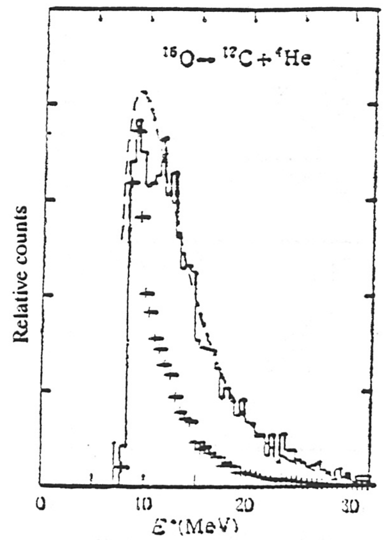

Fig.3
Distribution of excitation energy of primary products.

+ calculated from the energies of C and α-particles detected at neighboring angles. Histogram is the result after correction for kinematic effect. Dashed line is fitted Maxwellian distribution.

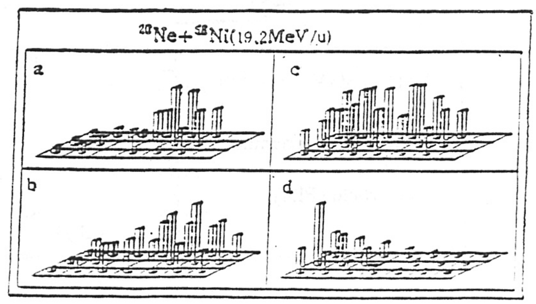

Fig.4
Coincident cross section distribution of correlated C and forward α-particles detected in 20 plastic scintillator detectors in 19.2 MeV/u ^{20}Ne + ^{58}Ni reaction.

a. Experimental result (C at −6°); b. Monte Carlo simulation result (C at −6°); c. Experimental result (C at −26°), d. Monte Carlo simulation result (C at −26°).

correlation between other projectile-like fragments and α-particles is quite similar to that in Fig.2. This means that in the close geometry the correlation events mainly result from sequential decay. However, limited by the kinematics, it is difficult to clarify the reaction mechanism leading to the correlation between projectile-like fragments and α-particles at distant geometry, even if the detected projectile-fragment and α-particle result from the sequential decay of one primary product.

Therefore, the study on the angular correlation distribution is quite important. For this purpose a Monte Carlo simulation program was developed to calculate the coincidence distribution for the sequential decay of the primary excited fragments. For simplicity, the reaction process is selected as follows:

$$^{20}\mathrm{Ne} + {}^{58}\mathrm{Ni} \longrightarrow {}^{16}\mathrm{O} + {}^{62}\mathrm{Zn} - 1.366\mathrm{MeV}.$$

$$^{16}\mathrm{O} \longrightarrow {}^{12}\mathrm{C} + \alpha - 7.162\mathrm{MeV}.$$

Three aspects should be considered in the Monte Carlo simulation program:

1) The angular correlation between the projectile-like fragment and α-particle is quite sensitive to the excitation energy distribution of the primary products, i.e., relative kinetic energy between the two secondary products. The relative kinetic energy between the two secondary decay products is equal to the difference between the excitation energy and threshold energy. It determines how far the two secondary products can move apart from each other in the velocity plane, and may affect strongly the angular correlation between them. In order to obtain the distribution of the excitation energy of the primary fragments, we sorted out the coincident events between projectile-like fragments ejected at 6° and α-particles detected in neighboring plastic scintillator PL10 (see Fig.1)

and calculated the relative kinetic energy between the two secondary decay products, under the assumption of the sequential decay, as shown in Fig.3 by + + + +. The actual distribution of primary fragment excitation energy was obtained only after the correction to the kinematic and geometric effects. The obtained result is shown in Fig.3 by histogram, which is nearly a Maxwellian distribution:

$$f(E_{rel}) = C \times \sqrt{E_{rel}} \times \exp\left(-\frac{E_{rel}}{T}\right), \tag{1}$$

where E_{rel} is the relative kinetic energy, and T is the temperature parameter (~4 MeV). The similar calculation results of the primary product excitation energy distribution were obtained for the coincident events by using other neighboring plastic scintillator detectors such as PL1, PL4, PL5, PL9 and PL11.

2) The energy and angular distributions of the primary products prior to the decay also should be considered in the simulation. This two-dimensional distribution is assumed to be a sum of three Gaussian distribution decaying with the ejection angle:

$$f(E,\vartheta) = \Sigma C_i \times \exp(-\mu_i \times \theta) \times \exp\left(-\frac{(E-E_i)^2}{2\sigma_i^2}\right). \tag{2}$$

where C_i, μ_i were selected to fit the inclusive experimental angular distribution of the projectile-like fragments, and E_i, σ_i were selected to fit the energy spectra of the secondary projectile-like fragments.

3) The α-particle emission was assumed to be isotropic in the center of mass system of primary reaction product.

In the Monte Carlo simulation, the angle and energy of primary fragment were sampled. Then, the relative kinetic energy was sampled according to Maxwellian distribution. The velocity vectors of the secondary products in the velocity plane can be calculated on the basis of momentum and energy conservation in the system of the primary product, the α-particle velocity direction being sampled according to the isotropic distribution. The velocity vectors of the two secondary products were transferred into the laboratory system. If they are emitted into the given angular region of the detectors as arranged in the experiment, the correlated kinetic energy and angular distributions can be obtained in the laboratory system. They can be compared with the experimental data directly. The results are shown in Fig.4.

The distributions of the angular correlation between the projectile-like fragments and α-particles detected by 20 plastic scintillator detectors in forward direction in 19.2 MeV/u ^{20}Ne + ^{58}Ni reaction are shown in the figure. The detection angles of the C products are –6° (left) and –26° (right), respectively. The experimental results are presented in the top two figures, while the Monte Carlo simulation results are given at the bottom. When the emission angle of the projectile-like fragments was small (–6°), the experimental coincident cross sections were enhanced at the opposite side of the projectile-like fragments relative to the beam direction, which can be reproduced by the Monte Carlo simulation calculation. This means the correlation events between the projectile-like fragments emitted in small angle and forward α-particles are mainly contributed by sequential decay of the primary reaction products.

But when the emission angle of the projectile-like fragments was moved to larger angle (–26°), the experimental distribution was bumped in the forward direction, which is quite different from the Monte Carlo simulation results. So there may be another reaction process, besides the sequential decay, that leads to this kind of correlations.

In the further study of the correlation events between the projectile-like fragments emitted in larger angles and forward α-particles, it was found that the distribution of the coincident cross sections was related to the product of two inclusive cross sections:

$$\left[\frac{d\sigma}{d\Omega_{plf}d\Omega_{\alpha}}\right]_{coin} = K \times \left[\frac{d\sigma}{d\Omega_{plf}}\right]_{incl} \times \left[\frac{d\sigma}{d\Omega_{\alpha}}\right]_{incl} \quad (3)$$

where K is nearly a constant.

In this case of coincidence the emissions of the projectile-like fragments and α-particles were correlated indirectly; we call it "uncorrelated" coincidence [9,10]. The possible reaction process is: the α-particle flied out to the forward direction at the early stage of the reaction, and the residual ^{16}O underwent a deeply dissipative process with the target nucleus. This dissipative process was independent of the α-particle. So the emission of the α-particles was correlated with the projectile-like fragments indirectly. We call this process "incomplete deep inelastic coilision" [11,12,13].

4. CONCLUSIONS

The correlation between forward α-particles and the projectile-like fragments emitted in different angles in ^{20}Ne + ^{58}Ni reactions has been measured. When the ejection angle of the projectile-like fragments is small (close to the grazing angle), the coincidence between the projectile-like fragments (mainly quasielastic) and α-particles can be interpreted by the sequential decay of the excited primary products, and the angular distribution of the correlation can be reproduced by the Monte Carlo simulation. When the projectile-like fragments are emitted into larger angles (mainly deeply dissipative projectile-like fragments), the coincidence between the projectile-like fragments and forward α-particles is "uncorrelated". It cannot be explained by the sequential decay of the excited primary products. The main reaction process leading to this kind of "uncorrelated" coincidence is a new heavy ion reaction process — "incomplete deep inelastic collision".

ACKNOWLEDGMENTS

The authors thank KVI of the Netherlands for providing the experimental conditions and Professor R.H. Siemssen for his helpful discussion and support.

REFERENCES

[1] Dayras, R., *J. de Physique*, C4(1986)13.
[2] Gregoire, C. and Tamain, B., *Ann. Phys. Fr.*, 11(1986)323.
[3] Goldhaber, A.S., *Phys. Lett.*, **53B**(1974)306.
[4] Gelbke, C.K. et al., *Phys. Rev. Lett.*, **70B**(1977)415.
[5] Gazes, S.B. et al., *Phys. Rev.*, **C38**(1988)712.
[6] Bizard, G. et al., *Phys. Lett.*, **172B**(1986)301.
[7] Steckmeyer, J.C., et al., *Nucl. Phys.*, **A500**(1989)372.
[8] Koldenhof, E.E., KVI Annual Report, 1986.
[9] Bhowmik, R.K. et al., *Phys. Rev. Lett.*, 43(1979)619.
[10] van Driel, J. et al., *Phys: Lett.*, **98B**(1981)351.
[11] Zhu Yongtai, et al., *Nucl. Phys.* **A488**(1988)409C.
[12] Guzman Martinez, F. and Reif, R., *Nucl. Phys.*, **A436**(1985)294.
[13] Terlau, W. et al., *Z. Phys.*, **A330**(1988)303.