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Observation of Light Particle Emission at Backward Angles in the Reaction Induced by 25MeV/u ^{6}He from ^{9}Be Target*

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Abstract Light particle emission at around 107° and 128° in the reaction induced by 25MeV/u ^{6}He from ^{9}Be target were clearly observed. The shape of the energy spectra obtained is consistent with an equilibrium evaporation from a source with a temperature of 5.6MeV or 5.2MeV for complete fusion or for incomplete fusion, respectively. A large number of tritons were detected compared to the number of protons, which may be related to the widely studied exotic cluster structure and the isospin effect of ^{6}He.

Key words energy spectra, fusion-evaporation, nuclear temperature

Fusion and evaporation is one of the major reaction mechanisms in the heavy ion reaction at low and intermediate energies. This kind of reaction is generally characterized by the energy and angular distribution of the emitted light particles[1—3]. With the invention of radioactive ion beam the study of nuclear reaction, including fusion and evaporation, has been expanded to a new domain. Over the past few years there have been intense studies of the fusion reaction induced by the neutron or proton rich nuclei at energies near the Coulomb barrier from the relatively heavy targets[4—6]. The exotic structure of the neutron rich nuclei, especially the halo nuclei, makes the reaction very different from the reaction with stable projectile. But at intermediate energies the experimental data for fusion-evaporation reaction are still very scarce. The reaction mechanism for stable nuclei at intermediate energies (around the Fermi energy) is characterized by the deep inelastic scattering (DIC), incomplete fusion and multi-source evaporation etc, which have been well understood based on the experiments with heavy ion beams. It is expected that some new phenomena for the reaction mechanism should be revealed if the exotic nuclear beams at intermediate energies were applied[7].

In this article we report an observation of the production of light particles at the backward angles from the reaction of halo nucleus ^{6}He of 25MeV/u with the ^{9}Be target. The energy spectra were analyzed by the evaporation model and some interesting phenomena were observed.

The experiment was carried out at the radioactive ion beam line RIPS at RIKEN (Fig.1). Primary beam of ^{13}C at 70MeV/u was used to bombard the thick Be target to produce the ^{6}He secondary beam through the projectile fragmentation process. By the combination of magnetic rigidity and energy loss analysis the ^{6}He at 25MeV/u were separated from other products. The particle identification was based on the $B\rho$-ΔE-TOF technique. Two plastic scintillation counters (0.5mm thick at F2 and 0.3mm thick at F3) were used to measure the time-of-flight (*TOF*), which was calibrated by using the primary beam at several energies. The energy loss (ΔE) was obtained by taking the analog signals of the plastic scintillation counters at F3. As shown in Fig.2 the ^{6}He nuclei can clearly be selected.

The secondary target was ^{9}Be of 100μm in thickness

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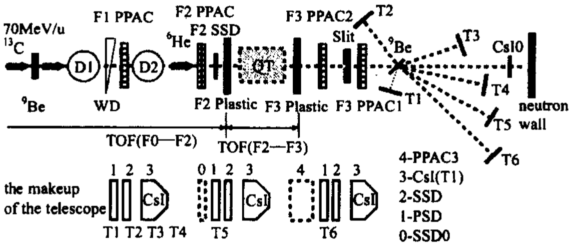

Fig.1. Schematic view of the experimental setup.

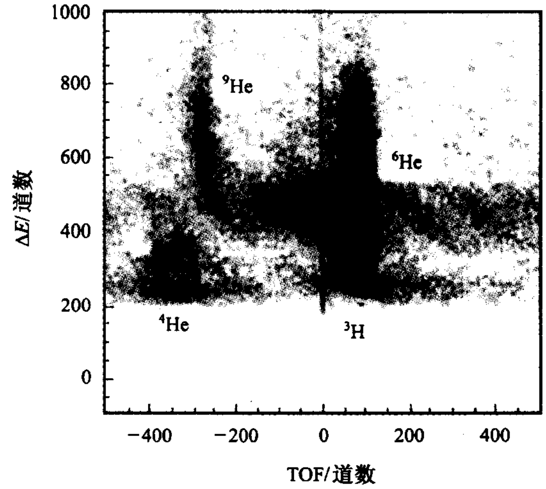

Fig.2. Particle identification.

and tilted at 45° relative to the beam direction. The effective area of the target was 30mm × 30mm. Two parallel plate avalanche counters (PPAC) were placed in front of the target to monitor beam intensity. A slit was placed in front of F3-PPAC1; with a hole of 20mm × 20mm, in order to limit the beam size. The outgoing charged particles produced from the Be target were detected by a set of 6 telescopes, each composed of a PSD (position sensitive silicon detector), a large area Si detector (SSD) and a CsI scintillation detector, as shown in Fig.1. T1 and T2 are the two telescopes located at backward angles of 107° and 128°, respectively, which were originally designed to detect the back scattered fragments which are coincide with the recoiled products at forward angles but may also be suitable to detect the evaporation particles. The energy calibrations of the telescopes were obtained by the standard method using ^{241}Am α source and precise pulse generator.

In Fig.3 is presented the two dimensional energy spectra for light particles detected by the telescope at 107°, where the isotopes of $Z = 1$ are well separated. These isotopes are subject to the selection of pure incident beam of ^{6}He based on the particle identification as shown in Fig.2. If we choose tritons in Fig.2 as the projectiles there is no $Z = 1$ isotopes presented in the spectra of the telescope 1 and 2. This means that the contamination of tritons in the incident beam can be neglected, especially when good selection condition was applied to the incident beam. It is also checked by applying an empty target that the background generated from material other than the physics target can also be neglected.

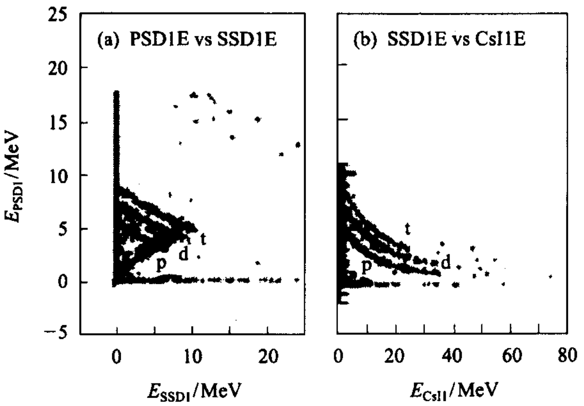

Fig.3. Two dimensional energy spectra for light particles detected by the telescope at 107°.

Kinetic-energy spectra of protons, deuterons and tritons produced in the reaction of ^{6}He at 25MeV/u with ^{9}Be target and detected by telescope 1 and 2 centered at 107° and 128°, respectively, are presented in Fig.4. It is interesting to see that the tritons are as many as the protons, which is in contrast to the general case where the proton and α particles dominate over deuterons and tritons[3]. The increase of the triton production may be related to the cluster structure of ^{6}He, which has been widely studied in past few years[8], reflecting the isospin effect of the halo nucleus. The energy spectra of the light particles all show exponential shape which in general corresponds to the equilibrium fusion-evaporation process[3]. We checked other possible source of these particles. Firstly the transfer of one triton from ^{6}He to the target was calculated by two-body kinematics, resulting in a much higher triton energy at the detected backward angles which could not be mixed to the currently observed energy spectra. Also at this intermediate energy the direct breakup, the pre-equilibrium particle emission or the deep inelastic scattering are also important, but the emission angle should be centered at forward direction and could not contribute to the data at backward angles. Therefore we may consider the dominance of the equilibrium evaporation process for the light particle emission at backward angles, and use the Maxwellian distribution to fit the energy spectra and to extract the nuclear temperature of the evaporation source. In the reference frame of the evaporation source the energy distribution of the emitted particles is[9]:

$$\frac{d^2\sigma}{dE d\Omega} = \sigma_0 E \exp\left(-\frac{E}{T}\right), \qquad (1)$$

where T is the nuclear temperature of the evaporation source and σ_0 the normalization constant. After transformation to the laboratory system the distribution becomes[10]:

$$\frac{d^2\sigma}{dE_{\mathrm{lab}} d\Omega} = \sigma_0[(E_{\mathrm{lab}} - V_x)E_{sx}]^{1/2}\exp\left(\frac{-E_{sx}}{T}\right), \qquad (2)$$

$$E_{sx} = E_{\mathrm{lab}} - V_x + E_0 - 2[E_0(E_{\mathrm{lab}} - V_x)]^{1/2}\cos(\theta_{\mathrm{lab}}), \qquad (3)$$

where E_{lab} is the kinetic energy of a fragment in the laboratory system and x indicates a kind of particle. E_{sx} represents the kinetic energy of a fragment in the evaporating source system and V_x the effective Coulomb barrier for the fragmentation. $E_0 = mv^2/2$ is the kinetic energy of the same fragment (with mass m) moving with the same velocity v as the evaporation source, The calculation also requires a specific definition of the fusion system. We firstly assume a complete fusion of the projectile and the target to form a ^{15}C. Then we consider the halo property of ^{6}He and assume that the two valence neutrons breakup before forming the fusion system of ^{13}C. Examples of the calculation are shown in Fig.4 and the obtained temperatures are listed in Tab.1. It is remarkable that temperatures obtained here are approximately the same for the emission particles at various angles. This phenomenon is consisted with the assumption of equilibrium fusion-evaporation. If the angular momentum of the fusion nucleus is neglected, the maximum temperature estimated[3] should attend 8.9MeV and 7.4MeV for ^{15}C and ^{13}C, respectively. The difference between the measured temperature and the estimated one comes from the transition of the incident energy to the rotational energy of the fusion system.

In summary, light particle emission at backward angles in the reaction of 25MeV/u ^{6}He with ^{9}Be were clearly observed, which corresponds to an equilibrium evaporation source with a temperature of about 5.6MeV for complete fusion or 5.2MeV for incomplete fusion. It is remarkable to see this phenomenon for such a light reaction system at intermediate energies. A large number of tritons were detected compared to the number of protons, which may be related to the exotic cluster structure and the isospin effect of ^{6}He. It is worthwhile to carry on more experiments to clarify these interesting phenomena.

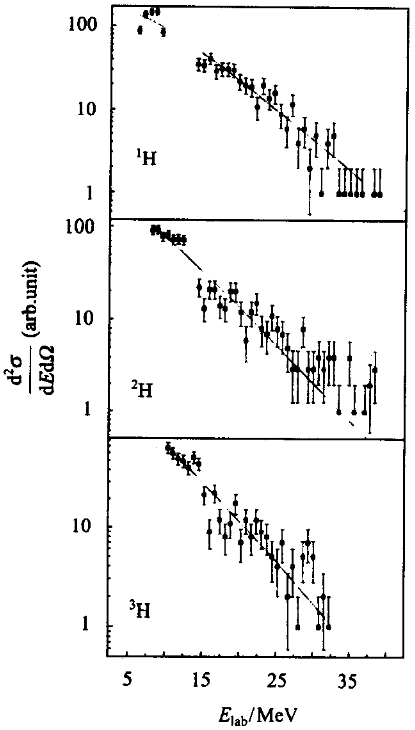

Fig.4. The energy spectra of three particles detected by the telescope at 107° and the fit with a Maxwellian function assuming a complete fusion system of ^{15}C.

Table 1. The nuclear temperature obtained from 25MeV/u ^{6}He + ^{9}Be reaction

^{15}C			
Detector		T/MeV	Mean value
^{1}H	107°	5.6 ± 0.3	$T = 5.6 \pm 0.1$ MeV
	128°	6.1 ± 0.3	
^{2}H	107°	5.2 ± 0.2	
	128°	6.1 ± 0.8	
^{3}H	107°	5.3 ± 0.3	
	128°	6.4 ± 1.0	

^{13}C			
Detector		T/MeV	Mean value
^{1}H	107°	5.3 ± 0.3	$T = 5.2 \pm 0.1$ MeV
	128°	5.6 ± 0.3	
^{2}H	107°	4.9 ± 0.2	
	128°	5.5 ± 0.7	
^{3}H	107°	4.9 ± 0.3	
	128°	5.7 ± 0.9	

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25MeV/u ^{6}He + ^{9}Be 反应的轻粒子发射*

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摘要 在25MeV/u ^{6}He与^{9}Be靶的反应中,107°和128°处明显地观察到了轻粒子发射. 粒子能谱形状与平衡热源蒸发相一致,分析得到热源的核温度为完全熔合条件下的5.6MeV或非完全熔合条件下的5.2MeV. 实验发现发射氚的数量特别大,这可能与目前广泛研究的^{6}He的集团结构和同位旋效应有关.

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