Binary decay fragment cross sections and prescission charge multiplicity in ^{84}Kr+^{27}Al at 10.6 MeV/nucleon

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The binary decay fragment cross sections and prescission charge multiplicity were measured in the reaction of ^{84}Kr+^{27}Al ($E_{\rm lab}$=10.6 MeV/nucleon) and compared with a statistical model calculation performed with the code GEMINI as a function of fission delay time. The comparison has suggested that a composite system may be formed at the point between the saddle and scission points and make a binary decay.

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A binary decay process in heavy ion reactions is considered a good tool to study the basic nuclear characteristics like nuclear viscosity. In such experiments the detection of prescission light particle evaporation in coincidence with binary decay fragments gives new information on the binary decay mechanism including its time scale; several experimental results are reported [1]. For the heavier mass system (mass $A\sim200$), a careful study of prescission multiplicity of neutrons, light charged particles (LCP's), and γ rays has concluded that the main binary decay is a slow and cold process [1–3]. Because the large prescission multiplicity cannot be reproduced by the standard statistical model calculation, analytical approaches have been performed by taking the dynamics of the reaction into consideration [4,5]. It is also suggested from the experimental results that the prescission particle evaporation takes place predominantly at larger deformation [6], that is, in between the saddle and scission points. The delay time of presaddle and postsaddle points gives an essential information for the nuclear dissipation.

For the lighter mass system, if a compound nucleus emits charged particles at the presaddle point, it tends to become an evaporation residue, because the critical angular momentum $J_{\rm er}$ which distinguishes evaporation and fission is very large (e.g., $J_{\rm er}\sim60\hbar$ for $A\sim100$) compared to the heavier system [7]. For this reason one can see the influence of prescission particle evaporation on the fragment cross sections more clearly with lighter mass systems than heavier ones.

In this paper we wish to suggest the mechanism of a binary decay in the lighter mass system ($A\sim100$) by comparing the measured cross sections and prescission LCP multiplicity with a statistical model calculation.

The experiment was performed using a large scattering chamber (ASCHRA) [8] at the RIKEN Accelerator Research Facility. A self-supporting Al target (600 μg/cm^2 in thickness) was bombarded with ^{84}Kr beams at the incident energy 10.6 MeV/nucleon. The details of the experiment and some of the results of the cross section measurement have been described in our previous paper [9]. In the coincidence measurement between binary fragments and LCP's, the heavy fragments were detected with a time-of-flight (TOF) counter telescope which consists of two channel plate detectors [10] and a large solid state detector ($\Delta\Omega\sim4$ msr). The TOF telescope was placed at 10° away from the beam axis. The flight path between the two channel plate detectors was 35 cm. The time resolution of the telescope was typically 300 ps. LCP's (Z=1 and 2) were detected with a 3π multidetector system. This system was composed of 120 phoswich detectors which could cover the angular range from 10° to 160° in the laboratory system. The phoswich detector consisted of a thin plastic scintillator (NE102A, 100 or 200 μm in thickness) and a thick (180 mm) BaF_2 crystal which has a good time response [11]. The flight paths were varied from 60 cm at a forward angle to 15 cm at a backward one. In order to determine the velocity of an emitted LCP directly, especially for the detectors placed at forward angles, we measured the TOF. The time difference between a rf signal of the cyclotron and a timing signal of a detector was used for the derivation of TOF. The phoswich detectors were calibrated using elastically scattered protons and alpha particles at the energy ranges of 10–20 and 15–30 MeV, respectively.

In order to study the dependence of prescission charge multiplicity on the coincident fragment mass, we have di-

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vided the observed fragment mass into two groups: one for symmetric binary decay products ($40<A<60$) and another for asymmetric mass division ($20<A<40$) which corresponds to the target mass region.

The energy spectra of the protons and alpha particles measured in coincidence with the heavy fragments were fitted by the moving source analysis in which three sources were assumed: a compound nucleus before scission and two fully accelerated fragments after scission. In the analysis the energy spectra of LCP's in the rest frame of the source were expressed by $W=E^{\hat{E}/t}\exp(-E/t)$ with $t=2T^2/(\hat{E}+T)$ [12]. Here $\hat{E}$ corresponds to the $B+T$, B and T being the evaporation barrier and temperature of an emitter, respectively. It is observed that alpha particles are emitted preferentially perpendicular to the spin direction of nuclei with a high angular momentum. Such a correlation too was included in the data analysis. The azimuthal distribution of particles emitted from a compound nucleus was assumed to be in the form $W(\phi)\propto\exp(\beta\sin^2\phi)$. Here θ and ϕ are the in-plane and out-of-plane detection angles, respectively. Positive θ denotes the angle of LCP detection in the same side as that of heavy fragments in reference to the beam axis. Further, ϕ is the angle between the direction of particle emission and the axis of spin of a compound nucleus. β was defined in the form $\beta\sim[(\hbar I)^2/(2\mathscr{T}T)][\mu R^2/(\mathscr{T}+\mu R^2)]$, where $\mathscr{T}$ is the moment of inertia of a compound nucleus, while I is the mean angular momentum for binary decay [13]. Using ten parameters, out of which seven define the shape (B_{cs}, T_{cs}, B_{ff1}, T_{ff1}, B_{ff2}, T_{ff2}, and ϕ, where the subscripts cs, $ff1$, and $ff2$ denote the compound nucleus, detected heavy fragment, and undetected one, respectively) and three are the multiplicities, we have fitted the spectra over the whole range of the in-plane and out-of-plane angles with a set of parameters. The values of (B,T) were obtained as (6.0, 4.5 MeV) for protons and (12.4, 4.5 MeV) for alpha particles. They are approximately 1 MeV lower than the empirical values listed in Ref. [14]. Figure 1 shows typical results of fittings. From this we can get the prescission and postscission LCP multiplicities. The prescission charge multiplicity corresponds to approximately 80% of the total charge multiplicity. We see no dependence of the prescission multiplicity on the division of mass asymmetry (see Table I.

A statistical model calculation has been performed using a code GEMINI [15]. The parameters used were essentially from Ref. [15]. The level density parameter a was taken as $A/10$ MeV^{-1}. The fission barrier for symmetric decay was taken from the rotating finite range model [16]. The excitation energy used was 200 MeV. The spin distribution of a compound nucleus was assumed to be given by a sharp cutoff approximation with the maximum angular momentum $l_{\max}=80\hbar$ at which the symmetric barrier vanishes. $80\hbar$

TABLE I. Multiplicity of the prescission and postscission evaporations for $Z=1$ and 2 particles.

	Prescission		Postscission	
	$Z=1$	$Z=2$	$Z=1$	$Z=2$
$20<A<40$	1.3±0.2	0.7±0.4	0.2±0.1	0.3±0.2
$40<A<60$	1.2±0.2	0.7±0.2	0.1±0.1	0.1±0.1

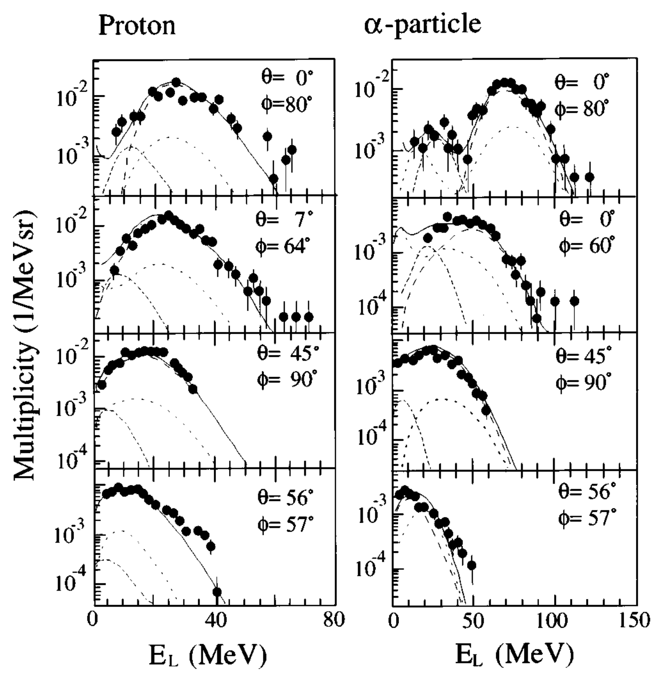

FIG. 1. Measured energy spectra of the light charged particles (LCP's) are shown by solid circles together with the results of three source fittings. The selected mass region of coincident heavy fragments is $40<A<60$. Postscission components from the detected fragments and those from undetected fragments, prescission contribution, and total spectra are shown, respectively, by short-dashed, dot-dashed, long-dashed, and solid lines. Here θ indicates the in-plane LCP detection angle. All θ's are in the same side as the TOF counter telescope for heavy fragment detection. On the other hand, ϕ denotes the out-of-plane detection angle and is defined by the angle between the direction of particle emission and the axis of spin of the compound nucleus.

agrees with our experimental result within the experimental error [9]. We have calculated the cross sections and particle multiplicity changing the fission delay time. The fission delay time is the time until which the fission decay width is taken as zero in the calculation. Figure 2 shows the results of the calculation of binary decay fragment cross sections, where the experimental data are shown by solid circles. Open circles were calculated without a fission delay time, while open squares and open triangles were calculated with the fission delay times of 5×10^{-21} and 2×10^{-20} s, respectively. In these calculations the fusion cross section was conserved at 990 mb, which is limited by $l_{\max}=80\hbar$.

Figure 3 shows the calculated results of prescission proton multiplicity (the left half) and the sum of binary decay fragment cross sections (the right half) for each mass region as a function of fission delay time. The experimental results are shown by solid lines together with the range of error by dashed lines. The calculations were performed for the prescission proton multiplicity using $a=A/9$ and $A/11$ MeV^{-1}. As for this parameter, an elaborate study has been done by Fineman *et al.* [17]. The ratio of the a's was taken as $a_f/a_\nu=1.0$. For the sum of the binary fragment cross sections, the ratio used was $a_f/a_\nu=1.0$ (solid circles) and=1.15 (open circles). The latter value corresponds to the ratio obtained with a_ν in the spherical shape and a_f at the saddle

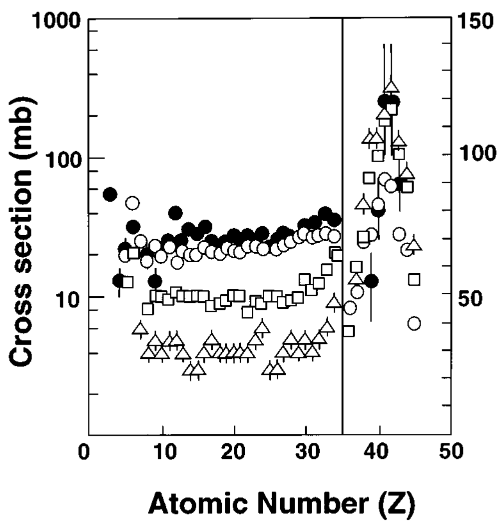

FIG. 2. Measured cross sections of the binary decay fragments are shown by solid circles. Open circles, squares, and triangles show the results of the statistical model calculations without a fission delay time, with 5×10^{-21} s delay and with 2×10^{-20} s delay, respectively. The y axis is in logarithmic scale for Z less than 36, while a linear scale for $Z\geqslant36$. $a_f/a_\nu=1.0$ is used. The total cross section was kept at 990 mb.

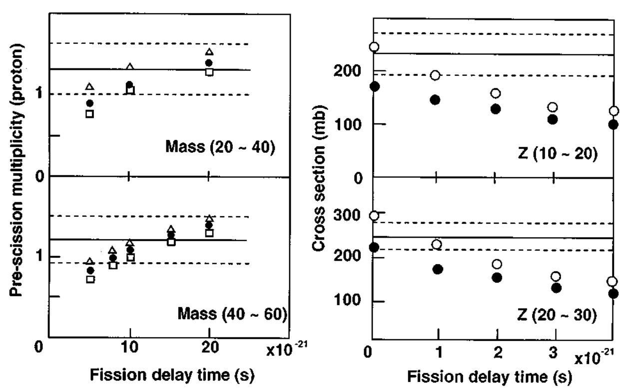

FIG. 3. In the left half, the calculated results of prescission proton multiplicity are shown as a function of fission delay time for two different mass regions. The experimental result is shown by the solid line with the corresponding error by dashed lines. Solid circles show the calculated results with $a=A/10$ MeV^{-1}, while open squares and triangles show the results for $a=A/9$ and $A/11$ MeV^{-1}, respectively. $a_f/a_\nu=1.0$ is used. In the right half, the sum of the binary decay fragment cross sections for two different atomic number regions is shown as a function of fission delay time. Solid circles are the calculated results of the statistical model calculation with $a=A/10$ MeV^{-1} and the ratio $a_f/a_\nu=1.0$. Open circles show the results with $a=A/10$ MeV^{-1} and $a_f/a_\nu=1.15$. The experimental results are shown by solid lines with the corresponding error by dashed lines.

point [18]. Even in the case of 1.15, the maximum fission delay time is approximately 1.5×10^{-21} s, which is one-tenth of the experimental prescission time. The calculations using $a=A/9$ and $A/11$ MeV^{-1} have also been performed for the sum of cross sections. The calculated values are not displayed here, but known to lay in between the open and solid circles in the right-half graph of Fig. 3.

The experimental cross section is well reproduced without a fission delay time. Without a fission delay time, however, the calculated prescission proton multiplicity is significantly smaller than the experimental value. To reproduce the prescission proton multiplicity, it is essential to introduce a fission delay time on the order of 10^{-20} s, even if we choose $a=A/11$ MeV^{-1}. However, an underestimation of the cross section of binary fragments is not negligible in this case. In a lighter mass system like ^{84}Kr+^{27}Al, a compound nucleus cannot undergo fission if it emits particles before choosing to go to fission because the large angular momentum is taken away by the evaporated particles. It is obvious from the difference of the cross sections calculated without a fission delay time and with a 5×10^{-21} s delay. Such a comparison suggests that the prescission protons are mainly emitted from the saddle to scission points: that is, the compound nucleus emits light particles after choosing to make a binary decay, as described in Ref. [6], and that otherwise this system does not go through the compound nucleus. That is, a composite system is formed at the point between the saddle and scission points.

For fissioning systems it is reported, based on a study of the prescission multiplicity as a function of the coincident fragment mass, that the asymmetric division occurs in the earlier stage of the reaction than the symmetric division [19,20]. In the present study, however, the prescission charge multiplicity was found to have no dependence on the exit channel mass asymmetry (see Ref. [21]). Taking both the different trends seen in references and the results of present study into account, the suggestion that the composite system formed at the point between the saddle and scission points makes a binary decay (fast fission) seems more probable. The actual fission barrier does not exist due to the effect of high angular momentum. The suggestion is also supported by the measured azimuthal angular distribution of alpha particles. The distribution indicates that the composite system has $\beta\sim1.5$, which was calculated using a mean angular momentum for binary decay, $J\sim74\hbar$. This β is smaller than that for a spherical system for which $\beta\sim3.0$.

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