

Symmetric mass-division process in nuclei with mass numbers around $A_{\text{CN}} = 100$

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Mass, angular, and total-kinetic-energy distributions for symmetric mass division products of the compound nucleus (CN) ^{105}Ag formed in the $^{37}\text{Cl} + ^{68}\text{Zn}$ and $^{16}\text{O} + ^{89}\text{Y}$ reactions have been measured with a time-of-flight telescope. The characteristics of the products are consistent with those of the fission products obtained in the heavier mass systems. A remarkable angular momentum effect on the width of the mass and total kinetic energy distributions is observed. The features of symmetric mass division products in nuclei with mass numbers around $A_{\text{CN}} = 100$ are summarized and systematically examined in terms of corresponding angular momentum.

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I. INTRODUCTION

The symmetric mass-division process of lighter compound nuclei (CN) with mass numbers around $A_{\text{CN}} = 100$ is little understood because it is difficult to identify the signatures of the process. In this mass region, it is of considerable interest to investigate the Businaro-Gallone (BG) limit based on the liquid-drop model [1]. For nuclei with fissility parameter x smaller than the BG limit $x_{\text{BG}} = 0.396$ and with a zero angular momentum, the saddle-point energy shows a maximum at symmetry in the mass-asymmetry coordinate; a deforming nucleus becomes unstable toward asymmetric deformation on its way from a saddle to a scission point. This saddle-point energy is called as the conditional barrier and the ridge-point potential-energy surface [2–4]. As angular momentum l brought into a compound nucleus increases, the conditional barrier decreases at mass symmetry and two BG mountains appear at the mass-asymmetry region. The angular momentum effect lowers the BG limit. This feature of the l -dependent potential-energy surfaces $B(l)$ is illustrated in Fig. 1 as a function of the mass asymmetry for the compound nucleus ^{105}Ag . The calculation of $B(l)$ is based on the liquid-drop model and will be discussed in Sec. III. The l -dependent yield $Y(l)$ in the compound-nucleus decay is expressed as

$$Y(l) \propto \exp[-B(l)/T_S(l)], \quad (1)$$

where $T_S(l)$ is the saddle-point temperature as defined in Sec. III. At high angular momentum, a symmetric mass division is expected even in light-mass systems with x smaller than x_{BG} .

Several experimental efforts have been made to confirm the symmetric mass-division process and to study features of the conditional barriers in nuclei lighter than

$A_{\text{CN}} \sim 100$. A binary symmetric mass division in these light composite nuclei formed by heavy-ion reactions has been verified with the coincidence method [5–15]. Yields of fissionlike products were reported by several authors [16–32], although certain ambiguities as to the nature of the products still remain. An experimental confirmation of the BG transition has also been extensively studied [33–43]. Few approaches, however, have been made to study the l dependence of mass and kinetic-energy distributions in this mass region.

The aim of the present work is to elucidate the presence of the symmetric mass-division process in light nuclei with mass numbers around $A_{\text{CN}} = 100$ and to study the role of angular momentum. In this paper we present the measured mass, angular, and total-kinetic-energy distributions of the products for the symmetric mass division of the ^{105}Ag formed in the $^{37}\text{Cl} + ^{68}\text{Zn}$ and the $^{16}\text{O} + ^{89}\text{Y}$ reactions. Since the two reaction systems produce the same compound nucleus ^{105}Ag , one expects to see the dependence of angular momentum and excitation energy on mass and kinetic-energy distributions of the symmetric mass-division products. Systematic features of mass and kinetic-energy distributions for the symmetric mass-division products in this mass region are examined in terms of the corresponding angular momentum. Part of this work has been published elsewhere [32].

II. EXPERIMENTAL PROCEDURES

Beams of ^{37}Cl with energies of 160 and 177 MeV and ^{16}O with 140 MeV from the JAERI (Japan Atomic Energy Research Institute) tandem accelerator were used to bombard self-supporting targets of ^{68}Zn (755 $\mu\text{g}/\text{cm}^2$ thick and 99.34% enrichment) and ^{89}Y (433 $\mu\text{g}/\text{cm}^2$ thick), respectively.

The mass distribution of the products was measured with a time-of-flight (TOF) telescope. The start detector was composed of a carbon foil (30 $\mu\text{g}/\text{cm}^2$ thick) micro-channel plate [44]. The stop and energy signals were delivered with a 250- $\mu\text{g}/\text{cm}^2$ -thick Si surface barrier detector located at about 65 cm from the start detector.

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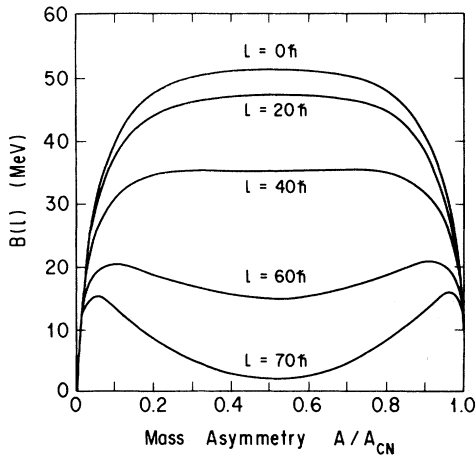


FIG. 1. Potential-energy surfaces at the saddle point for different angular momenta on the decay of the compound nucleus ^{105}Ag as a function of the mass asymmetry A/A_{CN} , where A_{CN} indicates the compound-nucleus mass number.

A fragment mass A was determined as $A \propto Et^2$ from the flight time t and the kinetic energy E corrected for pulse-height defect in a Si surface barrier detector. The pulse-height defect was estimated using the systematics of Moulton *et al.* [45].

The energy calibration was performed by using the elastically scattered projectiles from a $100\text{-}\mu\text{g}/\text{cm}^2$ -thick ^{197}Au target at high energies and α particles from an ^{241}Am source at low energy. The time calibration was carried out by a high-precision time calibrator. An overall time resolution of approximately 280 ps was achieved.

The data taken at various angles were normalized to the elastic scattering events at small angles.

III. RESULTS AND DISCUSSION

A. Experimental results and discussion

Measured mass distributions in the center-of-mass (c.m.) system are displayed in Figs. 2–4. The transformation of the mass distribution from the laboratory system to the c.m. system was carried out event by event using the method described in [46]. To obtain the primary mass fragments, corrections for neutron evaporation from fragments were made by assuming that the compound-nucleus excitation energy is shared between fragments in proportion to their masses [44,46] and that deexcitation of fragments occurs mainly via neutron evaporation and γ -ray emission [23]. Energies carried away via neutron and γ -ray emissions were assumed to be $2T$ and 10 MeV, respectively. The nuclear temperature T was given by $T = \sqrt{E_{\text{ex}}/a}$, with $a = A/8.5$. The excitation energy E_{ex} of a product mass A is expressed as

$$E_{\text{ex}} = (E_{\text{CN}}^* + Q - E_{\text{TKE}}) A / A_{\text{CN}}, \quad (2)$$

where E_{CN}^* and Q are the excitation energy of the com-

pound nucleus and the Q value for mass division. The total kinetic energy (TKE) of the fragments was obtained by assuming two-body kinematics.

As shown in Figs. 2 and 3, the products corresponding to the nucleon transfer reactions are located around the projectile mass A_P of ^{37}Cl and the target mass A_T of ^{68}Zn . These products strongly depend on the angle; the projectilelike products appear at more forward angles, while the bump of the targetlike recoil products is observed at backward angles. At forward angles $\theta_{\text{lab}} = 15^\circ$ and 20° , one can see the products of symmetric mass division apart from the nucleon transfer reaction products. Since we focus on the symmetric mass-division process, the mass distributions taken at these forward angles will be used in the following discussion. In the $^{16}\text{O} + ^{89}\text{Y}$ system shown in Fig. 4, the peak of the symmetric mass division is clearly seen, while the components of projec-

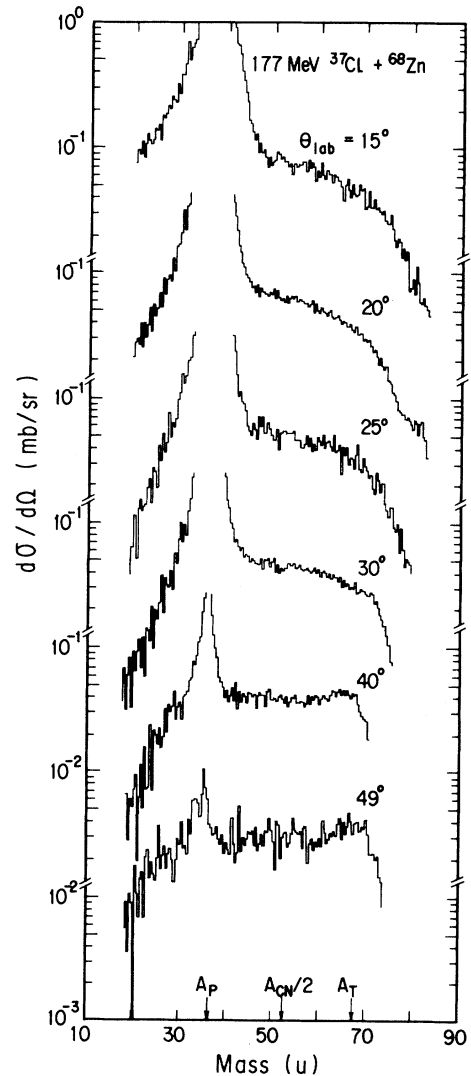


FIG. 2. Fragment mass distributions for the reaction 177 MeV $^{37}\text{Cl} + ^{68}\text{Zn}$. The symbols A_P and A_T correspond to the mass numbers of the projectile and target nucleus.

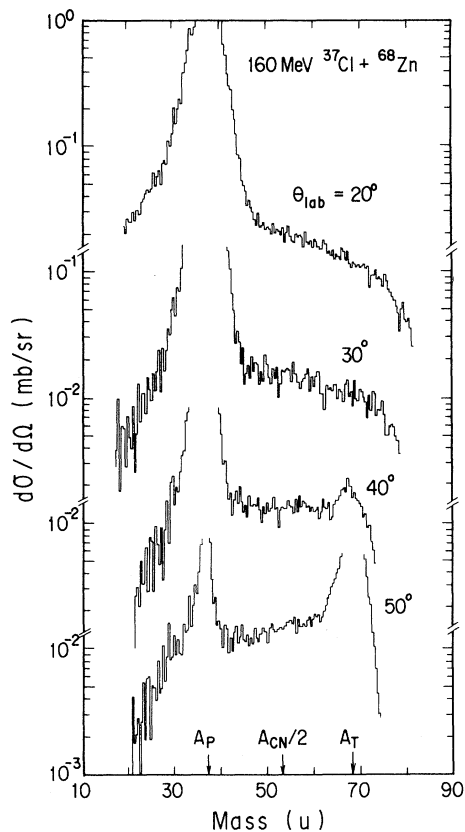


FIG. 3. Same as Fig. 2 for the reaction 160 MeV $^{37}\text{Cl} + ^{68}\text{Zn}$.

tilelike and targetlike products appear in the mass regions of $A \leq 40$ and $A \geq 65$, respectively.

Figure 5 shows the mass distributions for the symmetric mass-division products. To avoid the contaminants from projectilelike products, the mass distributions are cut off below $A \sim 50$ in the $^{37}\text{Cl} + ^{68}\text{Zn}$ system. As

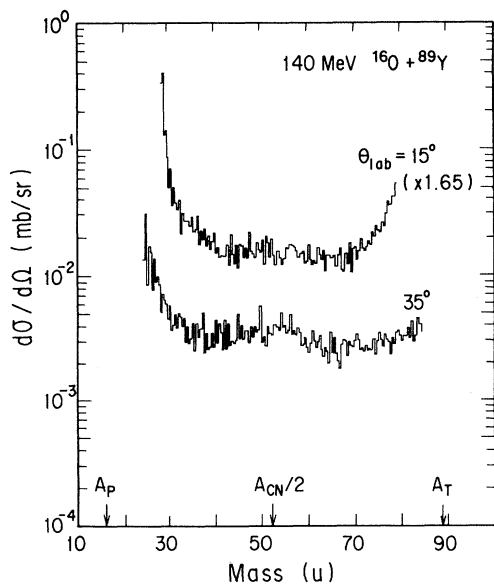


FIG. 4. Same as Fig. 2 for the reaction 140 MeV $^{16}\text{O} + ^{89}\text{Y}$.

shown in Figs. 5(a) and 5(b), no clear scattering angle dependence is observed in the symmetric mass region and there is no evidence for a peak around A_T . The dashed lines are a least-squares fit to the data by a Gaussian function having the center at $\frac{1}{2}A_{\text{CN}}$. In the $^{16}\text{O} + ^{89}\text{Y}$ system, a Gaussian fit was performed to the data at $\theta_{\text{lab}} = 35^\circ$.

In Fig. 6 are shown the angular distributions for the symmetric mass-division products. The differential cross sections for the $^{16}\text{O} + ^{89}\text{Y}$ system are obtained from the integration of the symmetric mass distributions, while those in the $^{37}\text{Cl} + ^{68}\text{Zn}$ are from the mass region $50 \leq A \leq 55$ to eliminate the contaminants from the nucleon transfer products. The angular distributions of the symmetric mass-division products are essentially flat in $d\sigma/d\theta_{\text{c.m.}}$, as expected for the fission products of the compound nucleus or the decay products of a long-lived

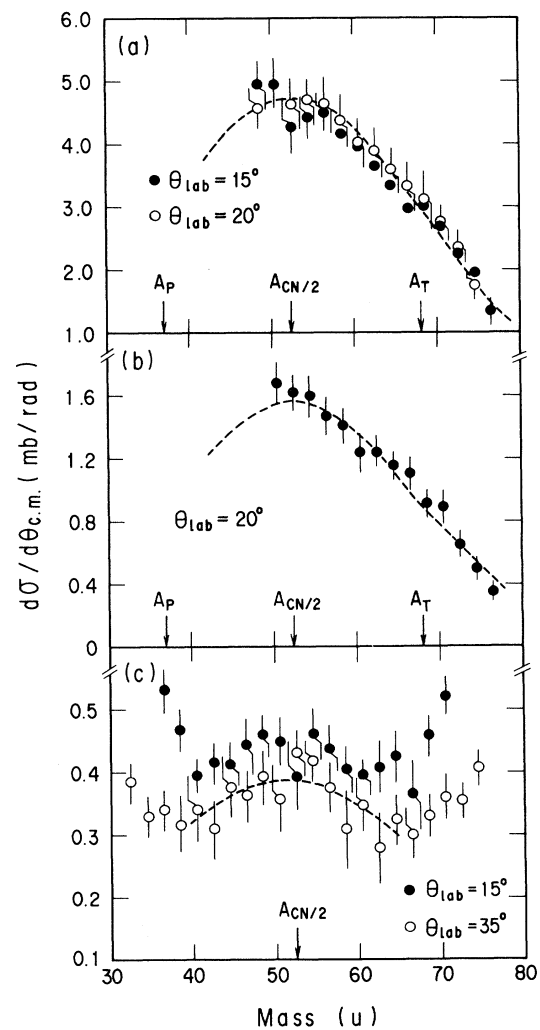


FIG. 5. Mass distributions for the symmetric mass-division products for (a) 177 MeV $^{37}\text{Cl} + ^{68}\text{Zn}$, (b) 160 MeV $^{37}\text{Cl} + ^{68}\text{Zn}$, and (c) 140 MeV $^{16}\text{O} + ^{89}\text{Y}$. The dashed lines are a least-squares fit by a Gaussian function.

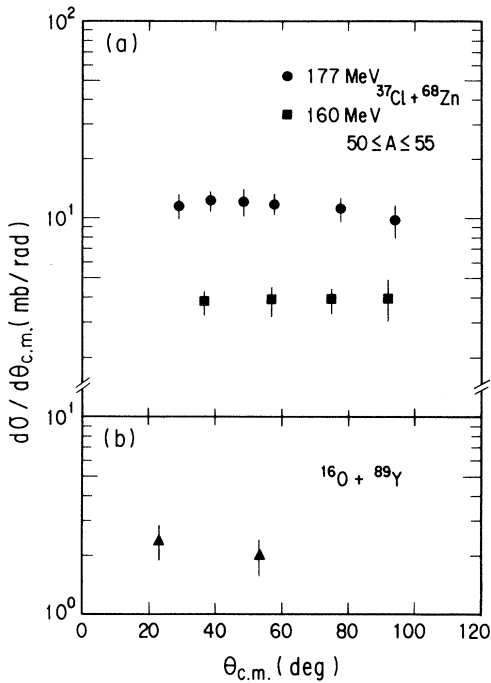


FIG. 6. Center-of-mass angular distributions for the symmetric mass-division products. The differential cross sections for the $^{16}\text{O} + ^{89}\text{Y}$ system are the integrated values of the mass distributions, while those in the $^{37}\text{Cl} + ^{68}\text{Zn}$ are from the mass region of $50 \leq A \leq 55$.

dinuclear system, indicating that the composite system has reached an equilibrium state in all the degrees of freedom prior to scission.

In Fig. 7 ratios of the cross sections σ_f for the symmetric mass-division products to the fusion cross sections σ_{CN} by the Bass model [47] are plotted as a function of the corresponding maximum angular momentum l_{max} . The angle-integrated cross sections σ_f were obtained by assuming an isotropic form of $d\sigma/d\theta_{c.m.}$ angular distributions. It is clearly seen that the ratio exponentially increases with l_{max} in the l region studied, indicating that the probability of the symmetric mass-division process strongly depends on l_{max} .

The experimental cross sections are compared with prediction of a statistical compound-nucleus model. The statistical-model analysis of fission decay has been carried out by means of the computer code PACE2 [48]. The angular momentum dependence of the fission barrier and the yrast line up to the maximum angular momentum [48] were taken from the rotating finite-range model (RFRM) of Sierk [49]. Fits to the data were made using the default parameters; the scaling factor k of the fission barrier that determines the slope of the calculated excitation function was 1.0, and the ratio of the level-density parameter for fission to that of particle emission α_f/α_v was set to unity. The fusion cross sections were obtained by using the Bass potential [47]. The comparisons between the experimental values and the calculations are shown in Fig. 8 as a function of the compound-nucleus

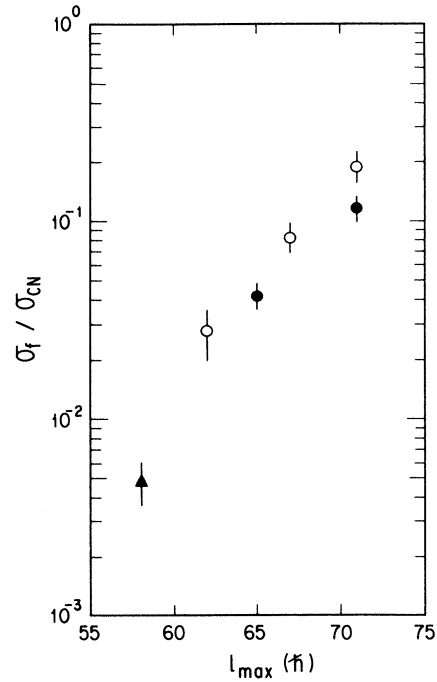


FIG. 7. Ratio of the cross sections σ_f for the symmetric mass-division process to the fusion cross sections σ_{CN} as a function of the corresponding l_{max} for the $^{37}\text{Cl} + ^{68}\text{Zn}$ (●) and the $^{16}\text{O} + ^{89}\text{Y}$ (▲) systems. The open symbols are taken from Ref. [14].

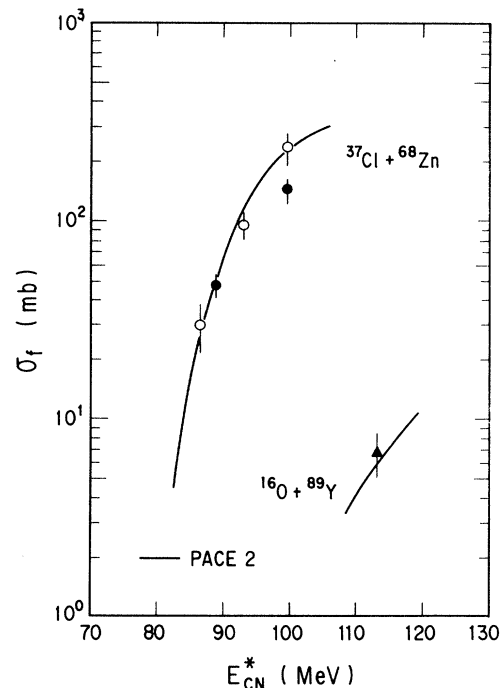


FIG. 8. Comparison of the experimental cross sections for the symmetric mass-division process and the calculated fission cross sections. The solid lines represent the calculated values with the PACE2 code [48]. The open symbols are taken from Ref. [14].

excitation energy. The figure shows that the experimental cross sections are well reproduced by the calculation, indicating that the observed symmetric mass-division processes are consistent with the statistical fission decay.

In Fig. 9 the mean total kinetic energy $\langle E_{\text{TKE}} \rangle$ and the variance σ_{TKE} of TKE distributions are plotted as a function of the c.m. scattering angle. The variances σ_{TKE} are obtained by assuming a Gaussian function for TKE distributions. The width of the fission-fragment TKE distribution is expected to broaden with the nuclear temperature T_S at the saddle point [50]. The experimental variances are reduced to the values at $T_S = 1.6$ MeV and $l = l_{\text{max}}$ [32],

$$\sigma_{\text{TKE}} = \sigma_{\text{TKE}}^{\text{expt}} / \sqrt{T_S(l_{\text{max}})/1.6}, \quad (3)$$

where l_{max} is the maximum angular momentum for fusion taken from the prediction of Bass [47]. Since the symmetric mass-division process is prominent at a higher- l region as discussed above, l_{max} will be used in the following discussion on l effects. The l -dependent saddle-point temperature $T_S(l)$ is given by [51,14]

$$\frac{1}{T_S(l)} = \left[\frac{a}{E_{\text{CN}}^*(l) - B_S(l)} \right]^{1/2} - \left[\frac{2}{E_{\text{CN}}^*(l) - B_S(l)} \right]. \quad (4)$$

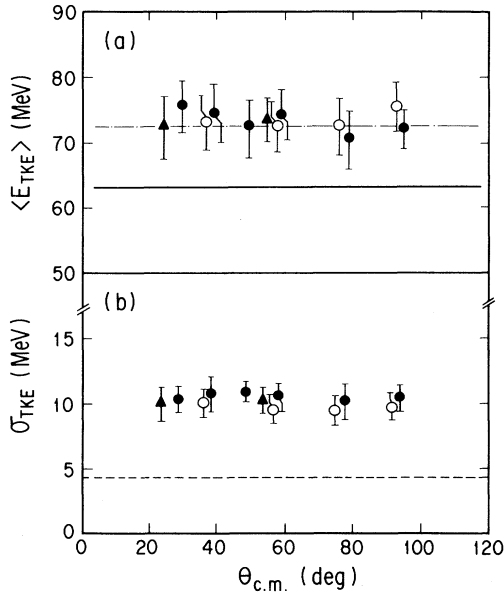


FIG. 9. Mean total kinetic energy $\langle E_{\text{TKE}} \rangle$ and variance σ_{TKE} of the TKE distributions as a function of the c.m. scattering angle for the 160 MeV $^{37}\text{Cl} + ^{68}\text{Zn}$ (\circ), 177 MeV $^{37}\text{Cl} + ^{68}\text{Zn}$ (\bullet), and 140 MeV $^{16}\text{O} + ^{89}\text{Y}$ (\blacktriangle). The solid and dot-dashed lines in (a) show the values expected from the empirical formulas of Viola, Kwiatkowski, and Walker [54] and [55], respectively. The dashed line in (b) indicates the predicted value of σ_{TKE} by the liquid-drop model of Nix [50] at the saddle-point temperature 1.6 MeV (see text).

The level-density parameter a is fixed as $a = A/8.5$ MeV $^{-1}$ [51]. The $E_{\text{CN}}^*(l)$ is l -dependent compound-nucleus excitation energy [14]:

$$E_{\text{CN}}^*(l) = E_{\text{c.m.}} + Q_{\text{gg}} - E_{\text{rot}}^{\text{CN}}(l), \quad (5)$$

with Q_{gg} representing the ground-state reaction Q value, $E_{\text{c.m.}}$ the bombarding energy in the c.m. system, and $E_{\text{rot}}^{\text{CN}}$ the rotational ground-state energy of a compound nucleus. The l -dependent potential energy $B(l)$ is [14]

$$B(l) = (U_1 + U_2 - U_{\text{CN}}) + U_C + U_N + [E_{\text{rot}}^{\text{SP}}(l) - E_{\text{rot}}^{\text{CN}}(l)], \quad (6)$$

where U_1 , U_2 , and U_{CN} are the liquid-drop masses [52] of fragments 1,2 and a compound nucleus. The Coulomb repulsion energy is denoted by U_C , and two touching spheres are assumed as the saddle-point configuration. The nuclear attractive force U_N of two fragments was obtained from the proximity potential [53]. The rotational energy of the saddle-point configuration, $E_{\text{rot}}^{\text{SP}}$, was calculated by assuming the sticking limit.

As shown in Fig. 9, $\langle E_{\text{TKE}} \rangle$ and σ_{TKE} are practically independent of the scattering angle. The dot-dashed and solid lines in Fig 9(a) show the expected values from the empirical formulas of Viola, Kwiatkowski, and Walker [54,55]. The systematics in the 1966 version reproduces well the present $\langle E_{\text{TKE}} \rangle$ values. These results show that the reactions considered are characterized by a fully kinetic-energy relaxation of the initial relative motion. No significant dependence on the corresponding angular momentum and excitation energy is observed in $\langle E_{\text{TKE}} \rangle$ and σ_{TKE} in the studied l and E_{CN}^* regions.

The dashed line in Fig. 9(b) indicates the value predicted from the liquid-drop model of Nix [50] in which the nuclear temperature at the saddle point is fixed to

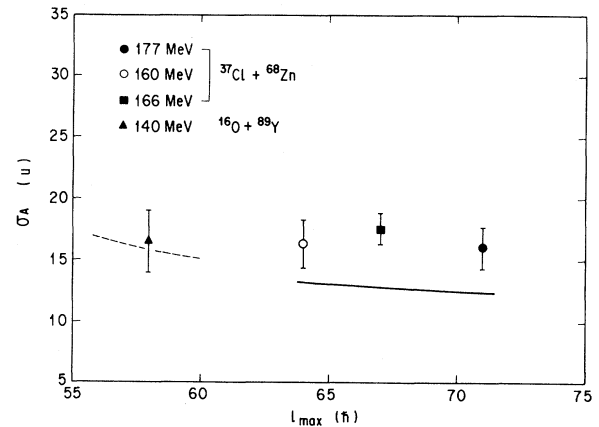


FIG. 10. Variances of the mass distributions for the symmetric mass-division process as a function of l_{max} . The internal excitation energy of the composite system is normalized to an excitation energy corresponding to $T_S(l_{\text{max}}) = 1.6$ MeV. The value for the 166 MeV $^{37}\text{Cl} + ^{68}\text{Zn}$ reaction (open circle) is taken from Ref. [14]. The solid and dashed lines are the variances predicted from the static-model calculation based on the potential-energy surfaces in Fig. 1 for the $^{37}\text{Cl} + ^{68}\text{Zn}$ and $^{16}\text{O} + ^{89}\text{Y}$, respectively.

$T_S = 1.6$ MeV. The experimental widths are considerably larger than the calculated widths. Similar results were reported in heavy-ion-induced fission of heavier-mass systems [56,57].

The measured variances σ_A^{expt} from the dashed lines in Fig. 5 at a nuclear temperature $T_S(l)$ are normalized to values corresponding to $T_S(l_{\text{max}}) = 1.6$ MeV as

$$\sigma_A = \sigma_A^{\text{expt}} \sqrt{T_S(l_{\text{max}})/1.6}. \quad (7)$$

In Fig. 10 the corrected σ_A values are plotted as a function of l_{max} . It is found that the σ_A values are independent of l_{max} in the studied l region. Assuming that the shape of the mass distribution depends only on that of the static potential-energy surfaces shown in Fig. 1, the width

of the corresponding mass distribution is expected to become narrower as angular momentum increases [58]. The solid and dashed lines are the calculated values expected from the static potential-energy surfaces for the systems $^{37}\text{Cl} + ^{68}\text{Zn}$ and $^{16}\text{O} + ^{89}\text{Y}$, respectively. The observed constancy of σ_A as a function of l is inconsistent with the prediction: the deviation of the experimental variances from the calculations increases with l_{max} . The same trend that the σ_A values are nearly independent of l_{max} was reported by Glagora, Back, and Betts [57] and Itkis *et al.* [59] in the mass region around $A_{\text{CN}} = 180-200$.

According to the consideration by Faber [60], the stiffness of the potential energy associated with the mass-asymmetry degree of freedom at a saddle point is expect-

TABLE I. List of the reactions studied in the present work with relevant parameters.

Reaction	Compound nucleus	x^a	E_{lab} (MeV)	E_{CN}^{*b} (MeV)	l_{max}^c (\hbar)	y^d	Reference
$^6\text{Li} + ^{40}\text{Ca}$	^{46}V	0.226	153	149	28	0.199	[9]
$^9\text{Be} + ^{40}\text{Ca}$	^{49}Cr	0.231	141	137	34	0.253	[9]
$^{12}\text{C} + ^{40}\text{Ca}$	^{52}Fe	0.255	186	156	45	0.386	[9]
$^{63}\text{Cu} + ^{12}\text{C}$	^{75}Br	0.324	794	132	39	0.124	[41]
$^{14}\text{N} + ^{58,60}\text{Ni}$	$^{(73)}\text{Br}$	0.331	126	~ 107	45	0.176	[5]
$^{32}\text{S} + ^{50}\text{Ti}$	^{82}Sr	0.349	140	84	54	0.194	[6]
$^{14}\text{N} + ^{\text{nat}}\text{Se}$	$^{(93)}\text{Nb}$	0.364	126	~ 121	50	0.126	[5]
$^{63}\text{Cu} + ^{27}\text{Al}$	^{90}Mo	0.386	794	234	71	0.269	[41]
$^{40}\text{Ca} + ^{40}\text{Ca}$	^{80}Zr	0.393	197	85.6	56	0.219	[15]
$^{93}\text{Nb} + ^9\text{Be}$	^{102}Rh	0.400	782	78	34	0.047	[38]
$^{12}\text{C} + ^{89}\text{Y}$	^{101}Rh	0.403	197	173	62	0.159	[16]
$^{35}\text{Cl} + ^{62}\text{Ni}$	^{97}Rh	0.407	170	95.2	66	0.196	[20]
$^{37}\text{Cl} + ^{68}\text{Zn}$	^{105}Ag	0.422	156	86.3	62	0.145	[14]
			160	88.9	65	0.159	present work
			166	92.8	67	0.169	[14]
			177	99.9	71	0.190	[14], present work
$^{16}\text{O} + ^{89}\text{Y}$	^{105}Ag	0.422	140	113.3	58	0.127	present work
$^{93}\text{Nb} + ^{12}\text{C}$	^{105}Ag	0.422	1060	121	51	0.098	[38]
			1367	156	59	0.131	[38]
			1674	191	66	0.164	[38]
$^{12}\text{C} + ^{98}\text{Mo}$	^{110}Cd	0.424	197	178	64	0.140	[16,17]
$p + ^{\text{nat}}\text{Ag}$	$^{(109)}\text{Cd}$	0.426	600	~ 240	26	0.024	[18,19]
$^{84}\text{Kr} + ^{24}\text{Mg}$	^{108}Cd	0.429	487	101	62	0.136	[24]
$^{32}\text{S} + ^{76}\text{Ge}$	^{108}Cd	0.429	158	101	67	0.159	[23]
			178	115	73	0.189	[23]
			198	129	79	0.221	[23]
			218	143	85	0.256	[23]
			225	148	87	0.268	[23]
$^{84}\text{Kr} + ^{27}\text{Al}$	^{111}In	0.436	496	108	64	0.137	[25]
$^{14}\text{N} + ^{\text{nat}}\text{Mo}$	$^{(110)}\text{In}$	0.438	126	~ 110	52	0.092	[5]
$^{45}\text{Sc} + ^{65}\text{Cu}$	^{110}Sn	0.453	200	94	70	0.165	[12]
$^{20}\text{Ne} + ^{100}\text{Mo}$	^{120}Te	0.457	146	118.2	64	0.115	[29]
$^{12}\text{C} + ^{\text{nat}}\text{Ag}$	$^{(120)}\text{I}$	0.472	107	~ 93	46	0.059	[16]
			197	~ 174	65	0.117	[16]
$^{20}\text{Ne} + ^{92}\text{Mo}$	^{112}Te	0.479	146	103.7	61	0.120	[29]
$^{14}\text{N} + ^{\text{nat}}\text{Ag}$	$^{(122)}\text{Xe}$	0.481	126	~ 112	54	0.078	[5]
$^{12}\text{C} + ^{116}\text{Sn}$	^{128}Ba	0.495	197	172	67	0.108	[16]

^aFissility parameter $x = (Z^2/A)/[50.883(1 - 1.7826I^2)]$, where $I = (N - Z)/A$. N , Z , and A are the neutron, proton, and mass numbers of the compound nucleus [61].

^bCompound-nucleus excitation energy.

^cMaximum angular momentum for fusion predicted by Bass [47].

^d $y = [1.9249/(1 - 1.7826I^2)]I_{\text{max}}^2/A^{7/3}$ [61].

ed to decrease with l . The mass distribution would become wider than predicted by the static potential-energy surface with l . The observed trend of σ_A in Fig. 9 would be qualitatively explained by this model.

Although the effect of l on σ_{TKE} and σ_A has not yet been fully accounted for in a quantitative manner, the observed broad width would be interpreted as a contribution of some dynamical effects including l to the symmetric mass-division process.

B. Systematics of symmetric mass-division process in nuclei with mass numbers around $A_{\text{CN}}=100$

The systematic features of symmetric mass-division products on cross sections, TKE, and mass distributions are discussed over a wide range of l_{max} . The reaction systems studied in this work are listed in Table I together with the relevant parameters.

Cross sections σ_f for the symmetric mass-division process are summarized in Fig. 11 as a function of corresponding l_{max} . The data are taken from Refs. [14, 19, 20, 23, 25, 29]. Except for the $p + {}^{\text{nat}}\text{Ag}$ system [19], the σ_f values increase smoothly with l_{max} and it seems to indicate the threshold of $l_{\text{max}} \sim 55\hbar$ for the symmetric mass division. According to the RFRM [49], the corresponding fission barrier B_f at $l_{\text{max}} \sim 55\hbar$ is about 10 MeV around the $A_{\text{CN}}=100$ region. It is nearly equal to the neutron binding energy of a compound nucleus. This

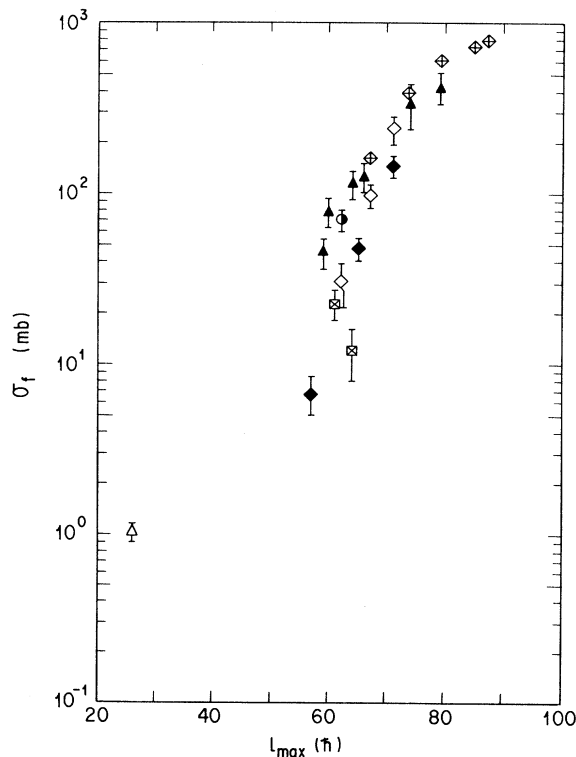


FIG. 11. Cross sections for the symmetric mass-division products as a function of corresponding l_{max} . The data are taken from Refs. [14] (\diamond), [19] (\triangle), [20] (\blacktriangle), [23] (\diamond), [25] (\bullet), [29] (\square), and the present work (\blacklozenge).

shows that the neutron evaporation process is dominant at $l_{\text{max}} < 55\hbar$, while the fission process competes with the evaporation beyond $l_{\text{max}} \sim 55\hbar$.

The $\langle E_{\text{TKE}} \rangle$ values observed in Refs. [5, 6, 9, 12, 14–16, 19, 20, 38, 41] are compared with the empirical formulas predicted by Viola, Kwiatkowski, and Walker [54,55] in Fig. 12. The experimental $\langle E_{\text{TKE}} \rangle$ values are well reproduced with the systematics in the 1966 version except for the data of Refs. [16,19]. Reevaluation of the formula by using the new data would be needed in the region around $Z^2/A^{1/3}=400\text{--}600$.

In Fig. 13 the corrected σ_{TKE} values corresponding to $T_S(l_{\text{max}})=1.6$ MeV are plotted as a function of l_{max} for the systems in Refs. [5, 6, 14, 19, 41]. As shown in Fig. 13, although the data are scattered, the σ_{TKE} tends to increase with increasing l_{max} in the indicated l_{max} region.

The σ_A values corrected by Eq. (7) taken from Refs. [5, 12, 14, 17, 19, 20, 23, 24, 29] are shown in Fig. 14 as a function of l_{max} . It can be seen that the mass distributions become wider with increasing l_{max} over a wide range of l_{max} . As discussed in the previous section, the stiffness of the potential energy associated with the mass-asymmetry degree of freedom at a saddle point is expected to decrease as l increases.

A dynamical model calculation associated with l is

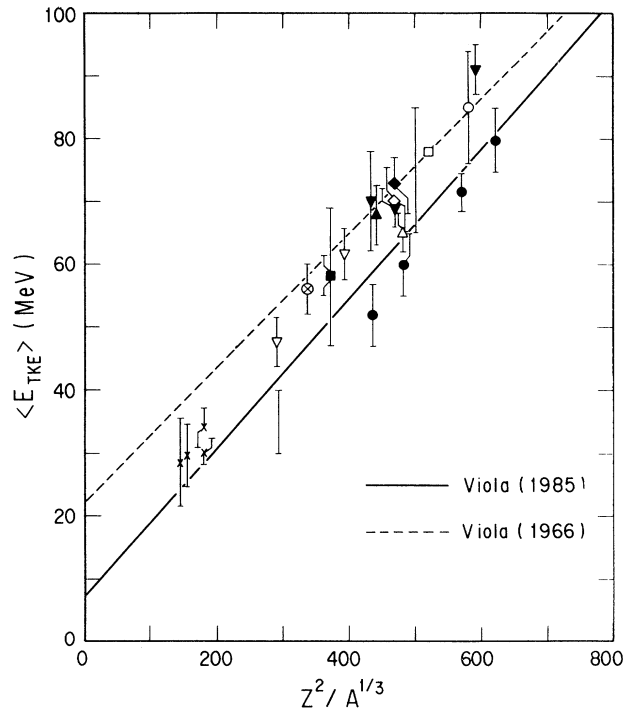


FIG. 12. Mean total kinetic energies for symmetric mass-division products taken from Refs. [5] (\circ and I), [6] (\otimes), [9] (\times), [12] (\square), [14] (\diamond), [15] (\blacksquare), [16] (\bullet), [19] (\triangle), [20] (\blacktriangle), [38] (\blacktriangledown), [41] (∇), and the present work (\blacklozenge) as a function of the Coulomb parameter $Z^2/A^{1/3}$ of fissioning nuclei. Empirical curves for fission kinetic-energy release are shown by solid [54] and dashed [55] lines.

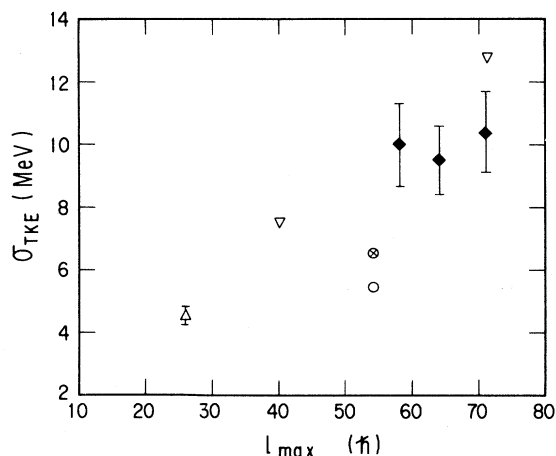


FIG. 13. Variances of TKE distributions for the symmetric mass-division products as a function of l_{\max} . The internal excitation energy of the composite system is normalized to an excitation energy corresponding to $T_S(l_{\max})=1.6$ MeV. The experimental σ_{TKE} are taken from Refs. [5] (\circ), [6] (\otimes), [14] (\diamond), [19] (\triangle), [41] (∇), and the present work (\blacklozenge).

needed to explain the widths of the total-kinetic-energy and mass distributions. Much more experimental and theoretical work is necessary before we attain a good quantitative understanding of the symmetric mass-division process in light systems.

IV. CONCLUSION

The observed mass, angular, and total-kinetic-energy distributions of the fully energy-damped symmetric mass-division products of ^{105}Ag formed in the reactions $^{37}\text{Cl} + ^{68}\text{Zn}$ and $^{16}\text{O} + ^{89}\text{Y}$ are consistent with those from the fission products in heavier-mass systems. The cross sections of these products are well reproduced by the statistical-model calculation. These results suggest that the products for the symmetric mass division originate from the symmetric fission of the compound nucleus. A significant angular momentum effect on the

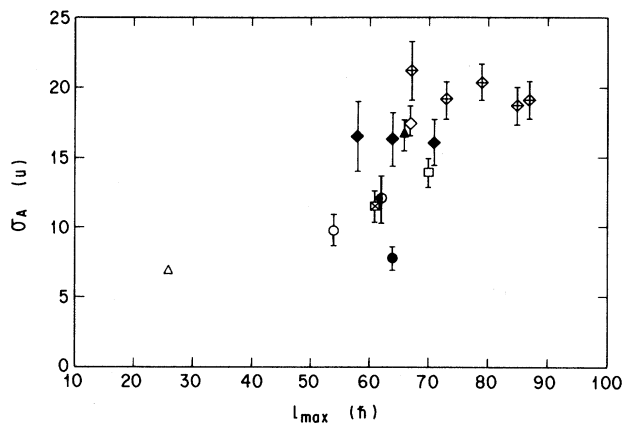


FIG. 14. Variances of the mass distributions for the symmetric mass-division products as a function of l_{\max} . The internal excitation energy of the composite system is normalized to an excitation energy corresponding to $T_S(l_{\max})=1.6$ MeV. The data are taken from Refs. [5] (\circ), [12] (\square), [14] (\diamond), [17] (\bullet), [19] (\triangle), [20] (\blacktriangle), [23] (\oplus), [24] (\odot), [29] (\boxtimes), and the present work (\blacklozenge).

mass and total-kinetic-energy distributions and cross sections has been observed. From the systematic interpretation on the characteristics of symmetric mass-division products in a wider range of angular momentum l , we confirm a remarkable l effect in the width of mass and TKE distributions and cross sections of symmetric mass-division products in nuclei with mass number around $A_{\text{CN}}=100$. The broad widths of the mass and TKE distributions cannot be accounted for the liquid-drop model. This feature should be explained by some dynamical effects including l at a saddle point.

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