Incomplete-fusion–fragmentation model: Multifragmentation data from 600*A* MeV heavy-ion collisions

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The incomplete-fusion–fragmentation model is modified to analyze ALADIN multifragmentation data of the projectile remnant in reactions of 600 MeV/nucleon Au on different targets. Since the incomplete-fusion–fragmentation model includes both the dynamical formation and the statistical disassembly of a hot nucleus, the ALADIN observables can be reproduced quite well when the model parameter concerning the excitation energy is somewhat adjusted to account for the mean multiplicity of intermediate mass fragments as a function of the total bound charge.

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I. INTRODUCTION

Multifragmentation of hot nuclei and the occurrence of intermediate mass fragments (IMF) in energetic nucleus-nucleus collisions have been widely investigated both experimentally [1–7] and theoretically [8–30]. Multifragmentation of a hot nucleus is characterized by the emission of more than two IMF's which are fragments with charge numbers $3 \leqslant Z_f \leqslant 30$. IMF is well suited for studying the onset of the multifragmentation decay mode of a hot nucleus, instead of the charge (mass) number of the reference fragment introduced in [27–30]. Theoretical studies of multifragmentation can be characterized mainly by the following: the dynamical approach [14–16], the statistical model [8–13,27], the percolation model [17–20], and a combination of statistical and dynamical calculations [21–26].

Although the dynamical simulation is very powerful in describing the space-time evolution of the reaction system, particle production, etc., it is not able to reproduce the yield of IMF's. The statistical model, on the other hand, has been very successful in describing the various distributions (e.g., mass, charge, and energy distributions) of fragments and the yields of IMF's. In fact, all of those successes could be regarded as evidence that the nuclear system has reached a certain state of thermal equilibrium. That fact is not commonly accepted, however, since thermal equilibrium is one of the basic assumptions of the statistical model. Whether the nuclear system approaches thermal equilibrium during the later stages of intermediate energy nucleus-nucleus collisions remains a subject of debate [31].

Recent published ALADIN data of correlations among the charges of fragments emitted from the projectile remnant in the reactions of 600 MeV/nucleon Au projectiles on different targets [32–36] strongly support the establishment of thermal equilibrium in the fragmenting nucleus (hot nucleus) before breakup. That has attracted, of course, great interest among theorists. Those correlations include the mean multiplicity of IMF's, the average charge of the largest fragment ($Z_{\max}$), the ratio of charge moments (γ_2), the asymmetry of the largest to second largest charge (a_{12}), and the three-body asymmetry parameter (a_{123}) as a function of Z_{bound} (which is the sum of the charges of fragments with $Z_f \geqslant 2$). All the aforementioned correlations are almost independent of the targets [33–35], the bombarding energies [36], and the measured techniques [37]; that can be taken as evidence for thermal equilibrium of the fragmenting nucleus before breakup.

There have been various attempts to analyze the ALADIN data with the statistical model, with a combination of dynamical and statistical calculations, and with the hybrid dynamical-percolation approach [38–41]. Since the presently available dynamical models do not allow for an unambiguous determination of the breakup condition of the fragmenting nucleus and the excitation energy, which always has been extracted as extremely high, the dynamical simulation is not able to reproduce the ALADIN data at the moment [35,42]. In Ref. [39] it was shown that if the input parameters of statistical calculations, i.e., the mass number and the excitation energy of the fragmenting nucleus, were determined by adjusting them so as to reproduce the mean IMF multiplicity as a function of average Z_{bound}, the remaining ALADIN data could be well reproduced by the statistical

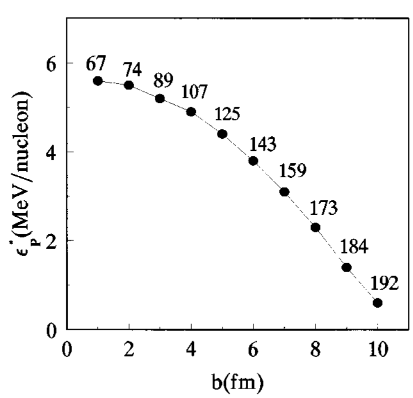

FIG. 1. The mass number and the excitation energy of projectile remnants as a function of impact parameter.

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model alone. A more accurate way of reproducing the ALADIN data was introduced in Refs. [35,38,40,41]. The calculation starts from a dynamical simulation (internuclear cascade model in Ref. [38], Boltzmann-Uehling-Uhlenbeck (BUU) model in Refs. [35,40,41]) and turns into statistical or percolation calculation (Moscow version of the Copenhagen model in Ref. [38], Berlin-Beijing model in Ref. [40], and percolation model in Refs. [41,35]) once the mass number and the excitation energy of the fragmenting nucleus have been properly defined from the dynamical simulation. However, one first needs to fit the correlation of $\langle M_{\mathrm{IMF}}\rangle$ vs $\langle Z_{\mathrm{bound}}\rangle$ by adjusting the excitation energy (in Refs. [35,40]) or the definition of the source (in Ref. [38]).

In this paper the proposed incomplete-fusion–fragmentation model (IFFM) [22,23,43,44], which has already had successes in describing the disassembly of a hot nucleus in intermediate energy nuclear collisions, has been improved somewhat to analyze the ALADIN data of disassembly of a projectile remnant (hot nucleus) in reaction of (600 MeV/nucleon) Au + Cu, for example. Since IFFM is a hybrid dynamical-statistical model, it turns out that only if the model parameter of the excitation energy of a fragmenting nucleus is slightly adjusted, due to the correlation of $\langle M_{\mathrm{IMF}}\rangle$ vs $\langle Z_{\mathrm{bound}}\rangle$, other observed correlations are all reproduced quite well.

II. MODEL DESCRIPTION

The experimental systematics of the longitudinal momentum transfer [45] have indicated that complete fusion gives way to incomplete fusion if the incident energy exceeds 8–10 MeV/nucleon. In the model it is assumed, therefore, that the formation of hot nuclei in intermediate energy nucleus-nucleus collisions is a dynamical incomplete fusion process.

Experiments also show that the fragments close to the target are formed in the peripheral interaction and low mass fragments in more central collisions. This enlightens us to rely on the participant-spectator picture in describing the formation of hot nuclei. We assume that the projectile remnant (hot nucleus) is composed of a part of projectile nucleons locating outside of the overlapping region between the target and the projectile nuclei under a given impact parameter. The target nucleons and the remains of projectile nucleons form the target remnant (another hot nucleus). The projectile nucleons located inside the overlapping region can be calculated as

$$N_P(b)=\rho_0\int dV\theta\{R_P-[x^2+(b-y)^2+z^2]^{1/2}\}\times\theta\{R_T-(x^2+y^2)^{1/2}\}, \tag{1}$$

where $\rho_0=0.16\ \mathrm{fm}^{-3}$ refers to the normal nuclear density, θ refers to the step function, R_P and R_T are, respectively, the radius of projectile and target nuclei, and b is the impact parameter. If one assumes further that the ratio of the charge to mass number of the projectile remnant is equal to the corresponding ratio of the projectile nucleus, as done in Refs. [35,38], the mass and charge numbers of the projectile and target remnants (A_P, Z_P, A_T, and Z_T) are then determined.

Since the incident energy is much larger than the Fermi motion energy or the nucleon interaction energy, it is reasonable to assume further that in the initial reaction stage the projectile spectator nucleons (missing mass, $A_P^0-N_P$, where A_P^0 refers to the mass number of the projectile nucleus) escape as a whole (projectile remnant) with beam velocity. The reaction energy Q can then be calculated from mass balance. From the energy and momentum conservations, the kinetic energy deposited in the reaction system (projectile and target remnants) can be derived as well. The sum of the deposited energy and the reaction energy is regarded as the available reaction energy of the system

$$E_{\mathrm{avai.}}=\frac{N_P}{A_P^0}\frac{A_T^0}{A_T^0+N_P}E_{\mathrm{in}}+Q, \tag{2}$$

where A_T^0 refers to the mass number of the target nucleus and E_{in} refers to the incident energy.

The available reaction energy is then shared among the projectile and target remnant nucleons with different weight parameters f_P and $f_T[=1+(1-f_P)A_p/A_T]$, respectively. The projectile remnant takes a share of

$$E_P=f_P\frac{A_P}{A_P+A_T}E_{\mathrm{avai.}}. \tag{3}$$

The excitation energy of projectile remnant can then be assumed as

$$E_P^*=C_P\times E_P, \tag{4}$$

where C_P is the fractional factor describing the part of energy E_P which turns into excitation energy. Since a certain portion of E_P should go to the expansion and the preequilibrium emission, C_P is less than 1. The excitation energy per nucleon is then

$$\epsilon_P^*=E_P^*/A_P. \tag{5}$$

As usual, one assumes that after expansion the aforeformed projectile (target) remnant approaches the freeze-out state, which is described as a sphere with radius parameter R_h ($h=P$ or T) greater than $r_0=1.18$ fm. R_h and $C_f^P=f_P\times C_P$ are regarded as model parameters.

The Berlin-Beijing model [10] is then used to describe the disassembly of the projectile remnant at freeze-out. In this model it was assumed that the projectile remnant (hot nucleus) disassembles promptly into a configuration described by a set of variables $\{N_c,N_n,\ \{A_i,Z_i\}_{i=1}^{N_c},\ \{\vec{r}_i\}_1^{N_c},\ \{\vec{p}_i\}_1^{N_c},\ \{\epsilon_i\}_1^{N_c},\ \{\vec{r}_j\},\ \{\vec{p}_j\}_1^{N_n}\}$. Here N_c refers to the number of charged fragments including prompt protons. N_n stands for the number of prompt and evaporated neutrons. $\{A_i,Z_i\}_{i=1}^{N_c}$, $\{\vec{r}_i\}_1^{N_c}$, $\{\vec{p}_i\}_1^{N_c}$, and $\{\epsilon_i\}_1^{N_c}$ are the set of mass and charge numbers, position, momentum, and internal excitation energy of charged fragments. $\{\vec{r}_j\}_1^{N_n}$ and $\{\vec{p}_j\}_1^{N_n}$ are the set of position and momentum of neutrons.

The configurations allowed by the mass, charge, momentum, and energy conservations were assumed to conform to a distribution of canonical or microcanonical ensemble [10]. By the means of the Monte Carlo method and the corre-

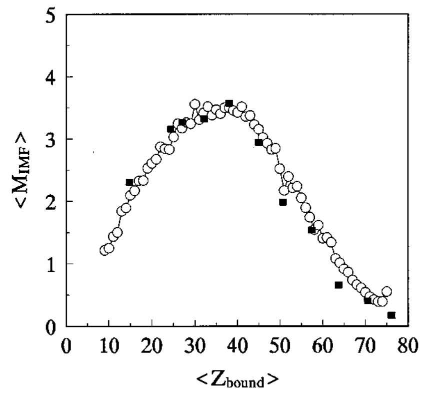

FIG. 2. Correlation between the average multiplicity of IMF ($\langle M_{\rm IMF}\rangle$) and the average total charge in bound fragments with charge number $Z_f \geqslant 2$. Open circles: the ALADIN data of the disassembly of projectile remnants in the reaction (600 MeV/nucleon) Au + Cu. Solid squares: results of IFFM.

sponding Metropolis pass a large number of allowed configurations (10^6, say) were generated and the physical observables could then be calculated as a statistical average.

III. RESULTS AND COMPARING WITH DATA

In Table I the results of N_P, N_T, A_P, Z_P, $E_{\rm avai.}$, E_P, E_P^*, and ϵ_P^* from the calculation of IFFM are given. The impact parameters are the same as those in Refs. [35,40,41]. It should be mentioned that the excitation energies per nucleon exhibited in Table I are the results from the adjustment to fit the observed correlation of $\langle M_{\rm IMF}\rangle$ vs $\langle Z_{\rm bound}\rangle$. The corresponding parameter $C_f^P(=f_P\times C_P=0.1\times 0.57)$ is equal to 0.057. We show in Fig. 1 ϵ_P^* as a function of the impact parameter b.

Figure 2 shows the correlation of $\langle M_{\rm IMF}\rangle$ vs $\langle Z_{\rm bound}\rangle$, where the open circles refer to the ALADIN data and the solid squares refer to the incomplete-fusion–fragmentation model calculations (the same labels are used in Figs. 3–7 as well). One learns from this figure that the mean multiplicity of IMF increases first with the decrease of $\langle Z_{\rm bound}\rangle$ (i.e., with the strength of violence of collision) and then begins to decrease after reaching a maximum at $\langle Z_{\rm bound}\rangle \sim 40$. This presents the evidence of the coexistence of a variety of decay modes of hot nuclei and the turning over of decay modes from the pseudoevaporation (or/and pseudofission) mode to the multifragmentation mode and then to the vaporization mode [27–30,46].

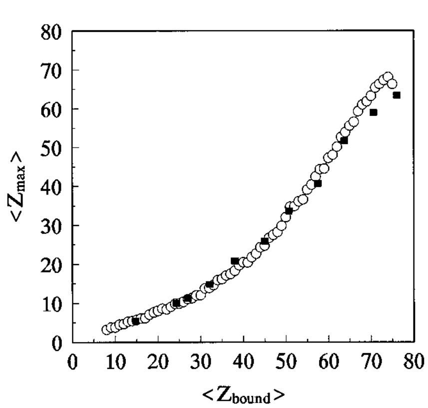

FIG. 3. The same as Fig. 2 but for the correlation between $\langle Z_{\rm max}\rangle$ and $\langle Z_{\rm bound}\rangle$.

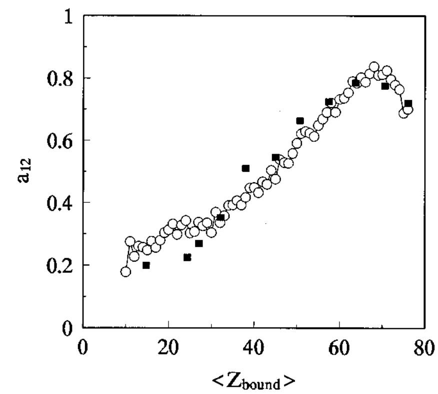

FIG. 4. The same as Fig. 2 but for the correlation between the asymmetry of two largest fragments and the $\langle Z_{\rm bound}\rangle$.

The distribution of $\langle Z_{\rm max}\rangle$ vs $\langle Z_{\rm bound}\rangle$ is shown in Fig. 3. Perfect agreement between the ALADIN data and the calculations can be seen here. Figure 3 exhibits that $\langle Z_{\rm max}\rangle$ decreases rapidly with $\langle Z_{\rm\ bound}\rangle$ decreasing. This means that the charges are shared by lighter fragments for the more violent collisions.

Figure 4 gives the asymmetry of the two largest fragments

$$a_{12}=\frac{Z_{\rm max}-Z_2}{Z_{\rm max}+Z_2}, \tag{6}$$

as a function of $\langle Z_{\rm bound}\rangle$, where Z_2 refers to the charge of the second largest fragment. The calculated results agree satisfactorily with the data. We show in Fig. 5 the same story for the second to third largest fragments,

$$a_{23}=\frac{Z_2-Z_3}{Z_2+Z_3}. \tag{7}$$

Quite good agreement is also obtained.

The result of three-body asymmetry

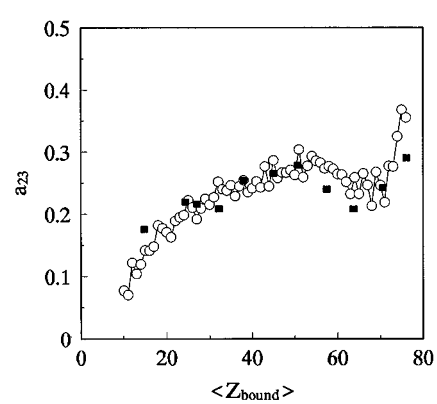

FIG. 5. The same as Fig. 2 but for the correlation between the asymmetry of the second and third largest fragments and the $\langle Z_{\rm bound}\rangle$.

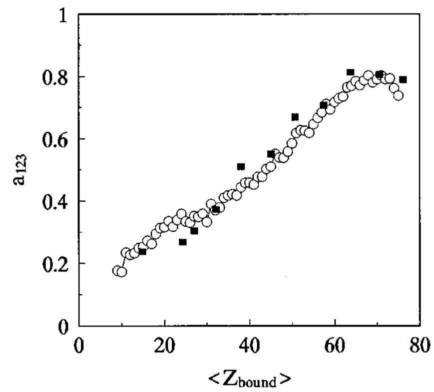

FIG. 6. The same as Fig. 2 but for the correlation between the three-body asymmetry and the $\langle Z_{\rm bound}\rangle$.

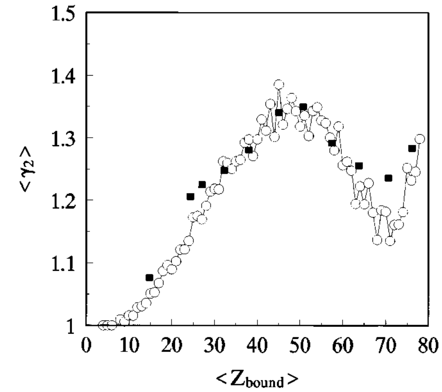

FIG. 7. The same as Fig. 2 but for the correlation between the ratio of charge moments, γ_2, and $\langle Z_{\rm bound}\rangle$.

$$a_{123}=\frac{\sqrt{[(Z_{\max}-\langle Z\rangle)^2+(Z_2-\langle Z\rangle)^2+(Z_3-\langle Z\rangle)^2]}}{\sqrt{6}\langle Z\rangle}, \quad (8)$$

is given in Fig. 6, where

$$\langle Z\rangle=\tfrac{1}{3}(Z_{\max}+Z_2+Z_3). \quad (9)$$

This varies smoothly with $\langle Z_{\rm bound}\rangle$ and reproduces the corresponding ALADIN data very well.

γ_2, the ratio of charge moment, is defined as

$$\gamma_2=\frac{\sigma_e^2}{\langle Z\rangle_e^2}+1 \quad (10)$$

and shown in Fig. 7. In the above equation σ_e^2 is the variance of the charge distribution within the event and $\langle Z\rangle_e^2$ is the mean charge of the event. γ_2 approaches its lower limit of 1 when all framents have the same charge; this may correspond to the pseudoevaporation or the vaporization decay mode of the disassembly of a hot nucleus. The mean value of γ_2 indicates the size of the charge fluctuations. Figure 7 shows that the ALADIN data of γ_2 are reproduced quite nicely.

IV. DISCUSSION AND CONCLUSION

First, it should be mentioned that Eq. (3) exhibits a relation between the excitation energy of a projectile remnant and its mass number. This results from adjusting the model parameter (C_f^P) to reproduce the correlation of $\langle M_{\rm IMF}\rangle$ vs $\langle Z_{\rm bound}\rangle$. We are pleased that the unified value of the $C_f^P=f_P\times C_P=0.1\times0.57=0.057$ is well fitted for all calculated projectile remnants; this is better than making an adjustment for every projectile remnant as done in Refs. [38–40].

It should be pointed out that the $C_P=0.57$, defined as a part of the parameter C_f^P and referred to as a fraction of the projectile remnant energy going into excitation energy, is somewhat smaller than corresponding values ($\sim0.6-0.8$) used in Refs. [22,23,43,44]. This is reasonable since the incident energy here is larger and the hot nucleus considered is the projectile remnant. The factor $f_P=0.1$ is close to the value of the rolling friction coefficient [47] in magnitude. This means that the process of transferring the available reaction energy into the projectile remnant might be regarded as a result of rolling friction when the projectile nucleus and target nucleus pass through each other. This is consistent with the participant-spectator picture adopted.

In summary, the IFFM it turns out is not only good for

TABLE I. The characteristics of projectile remnants in reaction (600 MeV/Nucleon) Au + Cu calculated from the incomplete-fusion–fragmentation model

b (fm)	N_T	N_P	A_P	Z_P	$E_{\rm avai.}$ (GeV)	E_P (MeV)	E_P^* (MeV)	ϵ_P^* (MeV/nucleon)
1	63	130	67	27	25.45	655.8	373.8	5.58
2	63	123	74	30	24.99	711.4	405.5	5.48
3	63	108	89	36	23.85	816.3	465.3	5.23
4	60	90	107	43	22.29	917.3	523.0	4.90
5	50	72	125	50	20.23	972.8	554.5	4.44
6	40	54	143	57	17.52	963.4	549.1	3.84
7	29	38	159	64	14.28	873.4	497.8	3.13
8	18	24	173	69	10.47	696.7	402.7	2.33
9	10	13	184	74	64.90	459.3	261.8	1.42
10	4	5	192	77	27.85	205.6	117.2	0.61

describing various distribution of fragments in disassembly of a hot nucleus but is also good for reproducing the ALADIN multifragmentation data, even though the dynamics involved in the IFFM is quite simple. This results because statistics plays a more important role than dynamics for describing the behavior of final fragments.

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[1] J. W. Harris *et al.*, Nucl. Phys. **A471**, 241c (1987).
[2] R. Trockel *et al.*, Phys. Rev. C **39**, 729 (1989).
[3] B. Jakobsson *et al.*, Nucl. Phys. **A509**, 195 (1990).
[4] K. Hagel *et al.*, Phys. Rev. Lett. **68**, 2141 (1992).
[5] L. G. Moretto, D. N. Delis, and G. J. Wozniak, Phys. Rev. Lett. **71**, 3935 (1993).
[6] V. Lips *et al.*, Phys. Rev. Lett. **72**, 1604 (1994).
[7] L. G. Moretto and G. J. Wozniak, Prog. Part. Nucl. Phys. **30**, 135 (1993).
[8] G. Bertsch and P. J. Siemens, Phys. Lett. B **126**, 9 (1983).
[9] J. Randrup and S. E. Koonin, Nucl. Phys. **A356**, 223 (1981); S. E. Koonin and J. Randrup, *ibid*. **A474**, 173 (1987); G. Fai and J. Randrup, *ibid.* **A487**, 397 (1988).
[10] Sa Ben-Hao and D. H. E. Gross, Nucl. Phys. **A437**, 643 (1985); Zhang Xiao-Ze, D. H. E. Gross, Xu Shu-Yan, and Zheng Yu-Ming, *ibid.* **A461**, 641 (1987); **A461**, 668 (1987); Y. M. Zheng, S. Y. Xu, X. Z. Zhang, and D. H. E. Gross, Chinese Phys. **10**, 146 (1990).
[11] J. P. Bondorf, R. Donangelo, I. N. Mishustin, C. J. Pethick, H. Schulz, and K. Sneppen, Nucl. Phys. **A443**, 321 (1985); J. P. Bondorf, R. Donangelo, I. N. Mishustin, and H. Schulz, *ibid.* **A444**, 460 (1985); H. W. Barz, J. P. Bondorf, R. Donangelo, I. N. Mishustin, and H. Schulz, *ibid.* **A448**, 753 (1986).
[12] W. A. Friedman and W. G. Lynch, Phys Rev. C **28**, 16 (1983).
[13] R. J. Charity *et al.*, Nucl. Phys. **A483**, 371 (1988).
[14] G. F. Bertsch and S. Das Gupta, Phys. Rep. **160**, 189 (1988).
[15] J. Aichelin, Phys. Rep. **202**, 233 (1991).
[16] Zheng Yu-Ming, Sa Ben-Hao, and Zhang Xiao-Ze, Chinese Phys. Lett. **6**, 117 (1989); L. De Paula, J. Nemeth, B. H. Sa, S. Leray, C. Ngô, H. Ngô, S. R. Souza, and Y. M. Zheng, Phys. Lett. B **258**, 251 (1991).
[17] W. Bauer, D. R. Dean, U. Mosel, and V. Post, Phys. Lett. **150B**, 53 (1985); W. Bauer, Phys. Rev. C **38**, 1297 (1988); W. Bauer and C.-K . Gelbke, Annu. Rev. Nucl. Sci. **42**, 77 (1992).
[18] X. Campi, J. Phys. A **19**, L917 (1986); Phys. Lett. B **208**, 351 (1988); J. Desbois, Nucl. Phys. **A466**, 724 (1987).
[19] T. Biro, J. Knoll, and J. Richert, Nucl. Phys. **A459**, 692 (1986).
[20] H. Ngô, C. Ngô, F. Ighezou, J. Desbois, S. Leray, and Y. M. Zheng, Z. Phys. A **337**, 18 (1990).
[21] K. Sneppen and L. Vinet, Nucl. Phys. **A480**, 342 (1988).
[22] Sa Ben-Hao, Zheng Yu-Ming, and Zhang Xiao-Ze, Phys. Rev. C **40**, 2680 (1989).
[23] Zheng Yu-Ming, Chih Ta-Hai, Li Wen-Xin, Zhang Xiao-Ze, and Sa Ben-Hao, Chinese J. Nucl. Phys. **14**, 116 (1992).
[24] A. S. Botvina, A. S. Iljinov, and I. N. Mishustin, Nucl. Phys. **A507**, 649 (1990).
[25] S. Leray, C. Ngô, M. E. Spina, B. Remaud, and F. Sebille, Nucl. Phys. **A511**, 414 (1990).
[26] M. Colonna, P. Roussel-Chomaz, N. Colonna, M. Di Toro, L. G. Moretto, and G. J. Wozniak, Phys. Lett. B **283**, 180 (1992).
[27] Y. M. Zheng, H. Massmann, S. Y. Xu, D. H. E. Gross, X. Z. Zhang, Z. Q. Lu, and B. H. Sa, Phys. Lett B **194**, 183 (1987).
[28] D. H. E. Gross, Zheng Yu-Ming, and H. Massmann, Phys. Lett. B **200**, 397 (1988).
[29] Sa Ben-Hao, Zheng Yu-Ming, and Zhang Xiao-Ze, Int. J. Mod. Phys. A **5**, 843 (1990).
[30] Sa Ben-Hao, Zheng Yu-Ming, and Zhang Xiao-Ze, Nucl. Phys. **A509**, 499 (1990).
[31] Sa Ben-Hao, Wang Rui-Hong, Zhang Xiao-Ze, Zheng Yu-Ming, and Lu Zhong-Dao, Phys. Rev. C **50**, 2614 (1994).
[32] C. A. Ogilvie *et al.*, Phys. Rev. Lett. **67**, 1214 (1991).
[33] J. Hubele *et al.*, Z. Phys A **340**, 263 (1991).
[34] J. Hubele *et al.*, Phys. Rev. C **46**, R1577 (1992).
[35] P. Kreutz *et al.*, Nucl. Phys. **A556**, 672 (1993).
[36] W. Trautmann *et al.*, GSI Report No. 93-76 1993; (unpublished); also GSI 05-94, 1994 (unpublished).
[37] P. L. Jain, G. Singh, and A. Mukhopadhyay, Phys. Rev. C **50**, 1085 (1994).
[38] A. S. Botvina and I. N. Mishustin, Phys. Lett B **294**, 23 (1992).
[39] H. W. Barz. W. Bauer, J. P. Bondorf, A. S. Botvina, R. Donangelo, H. Schulz, and K. Sneppen, Nucl. Phys. **A561**, 466 (1993).
[40] Bao-An Li, A. R. DeAngelis, and D. H. E. Gross, Phys. Lett. B **303**, 225 (1993).
[41] Y. M. Zheng, J. Richert, and P. Wagner, Chin. J. Nucl. Phys. **17**, 215 (1995).
[42] M. B. Tsang *et al.*, Phys. Rev. Lett. **71**, 1502 (1993).
[43] Chih Ta-Hai, Sa Ben-Hao, Zhang Xiao-Ze, and Zheng Yu-Ming, Phys. Rev. C **42**, 2187 (1990).
[44] W. X. Li, T. Y. Sun, T. H. Chih, Y. S. Li, Y. M. Zheng, R. L. Sun, L. L. Zhao, D. Q. Wu, G. M. Jing, and B. H. Sa, Phys. Rev C **48**, 628 (1993).
[45] V. Viola, Jr., B. B. Back, K. L. Wolf, T. C. Awes, C. K. Gelbke, and H. Breuer, Phys. Rev. C **26**, 178 (1982); Y. Chan, M. Murphy, R. G. Stokstad, I. Tserruya, and S. Wald, *ibid*. **27**, 447 (1983).
[46] Sa Ben-Hao, Nucl. Phys. **A499**, 480 (1989).
[47] H. J. Gray and Alan Isaacs, A *New Dictionary of Physics* (Longman Group Limited, England, 1975).