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Target effects in isobaric yield ratio differences between projectile fragmentation reactions

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Background: The isobaric yield ratio difference (IBD) between reactions is know to be sensitive to the density difference between projectiles in heavy-ion collisions around the Fermi energy.
Purpose: The target effects in the isobaric yield ratio (IYR) and the IBD results have been studied.
Methods: The amount of isotopes in the 140*A* MeV ^{48,40}Ca + ^{181}Ta/^{9}Be and ^{58,64}Ni + ^{181}Ta/^{9}Be reactions have been previously measured with high accuracy. The IYR and IBD results have been obtained from these reactions to study the effects of the light ^{9}Be and heavy ^{181}Ta targets. A ratio ($r_{\Delta\mu}$) between the IBD results for the reactions with Ta and Be targets is defined to quantitatively show the target dependence of the IBD results. Results The IYRs for reactions with symmetric projectiles are more easily affected than those for reactions with neutron-rich projectiles. The IBD results are suppressed by using the ^{181}Ta target to different degrees.
Conclusions: The IYR and IBD results are influenced by the target used. The IBD for the $I = 1$ isobaric chain is suggested as a probe to study the difference between the neutron and proton densities of the reaction systems.

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I. INTRODUCTION

The investigation of nuclear symmetry energy has been an important area of research in nuclear physics [1]. Many probes have been proposed to determine the nuclear symmetry energy of nuclear matters ranging from subsaturation to suprasaturation densities. Among these probes, the isobaric yield ratio difference (IBD) probe is known to be sensitive to nuclear density [2–5]. The isobaric yield ratio (IYR) provides cancelations of special energy terms in the free energy of fragments, which have been used to study the symmetry energy of fragments [6–10]. Similar to the isoscaling method [11–14], the IBD probe is constructed from the IYRs for two reactions of similar measurements. Both the IBD and isoscaling probes aim to measure the nuclear symmetry energy or density of nuclear matters in the range of subsaturation densities, and the results of IBD and isoscaling have been found to be similar [2,3].

The yield of fragments depends on the isospin of the reaction system, but the dependence decreases and even can disappear in fragments that have a small mass number [15–21]. The probes based on the fragment yield may depend on the asymmetry (N/Z) of the reaction system, such as the isoscaling parameters. Potentially, the IBD results should depend on the asymmetry of the projectile and target nuclei. The IBD probe can indicate the difference between the densities of reactions induced by projectiles with different asymmetry [2–5]. The amounts of isotopes produced in the 140*A* MeV ^{48,40}Ca + ^{181}Ta/^{9}Be and ^{58,64}Ni + ^{181}Ta/^{9}Be reactions have been measured with high precision by Mocko *et al.* at the National Superconducting Cyclotron Laboratory (NSCL), Michigan State University [22]. These high quality data have been studied extensively for different purposes [2,8,9,15,16,23–28]. The IYRs in these reactions have been used to study the symmetry energy coefficients of fragments [8,9,29,30] or temperature [23,24]. The IBD results for the reactions with the ^{9}Be target are known to be sensitive to the density difference between the projectiles [2]. Compared to ^{9}Be, the asymmetry of ^{181}Ta is $N/Z = 1.41$, which will introduce large asymmetry into the reaction system. It is interesting to study the target dependence of the IBD probe. In this article, the IBD results for reactions with the ^{181}Ta target are calculated, and the results are compared to those for reactions with the ^{9}Be target to investigate the target effects in the IBD method.

II. METHOD

The IYR differing 2 units in neutron-excess $I(I = N - Z)$ is defined as

$$R(I+2,I,A) = \sigma(I+2,A)/\sigma(I,A), \tag{1}$$

where σ is the yield of fragment and A is the mass of fragment. The IBD between two reactions of similar measurements is defined as

$$\mathrm{IBD} = \ln[R_2(I+2,I,A)] - \ln[R_1(I+2,I,A)], \tag{2}$$

with the indices 1 and 2 denoting the reaction systems. In the grand-canonical ensemble theory within the grand-canonical limit [31,32], or in a modified Fisher model [6,10,33], the IBD can be related to the chemical potential difference between neutrons and protons [2,3]:

$$\begin{aligned}\mathrm{IBD} = \Delta\mu/T &= (\Delta\mu_{n21} - \Delta\mu_{p21})/T,\\ &= [(\mu_{n2} - \mu_{n1}) - (\mu_{p2} - \mu_{p1})]/T,\\ &= \alpha - \beta,\end{aligned} \tag{3}$$

where μ_n (μ_p) is the chemical potential of neutrons (protons), which depends on the neutron (proton) density and temperature T. T is assumed to be the same in the two reactions. The chemical difference between neutrons and protons obtained from the IBD is called the IB–$\Delta\mu/T$. α (β) is the isoscaling parameter extracted from the isotopic (isotonic) ratio between

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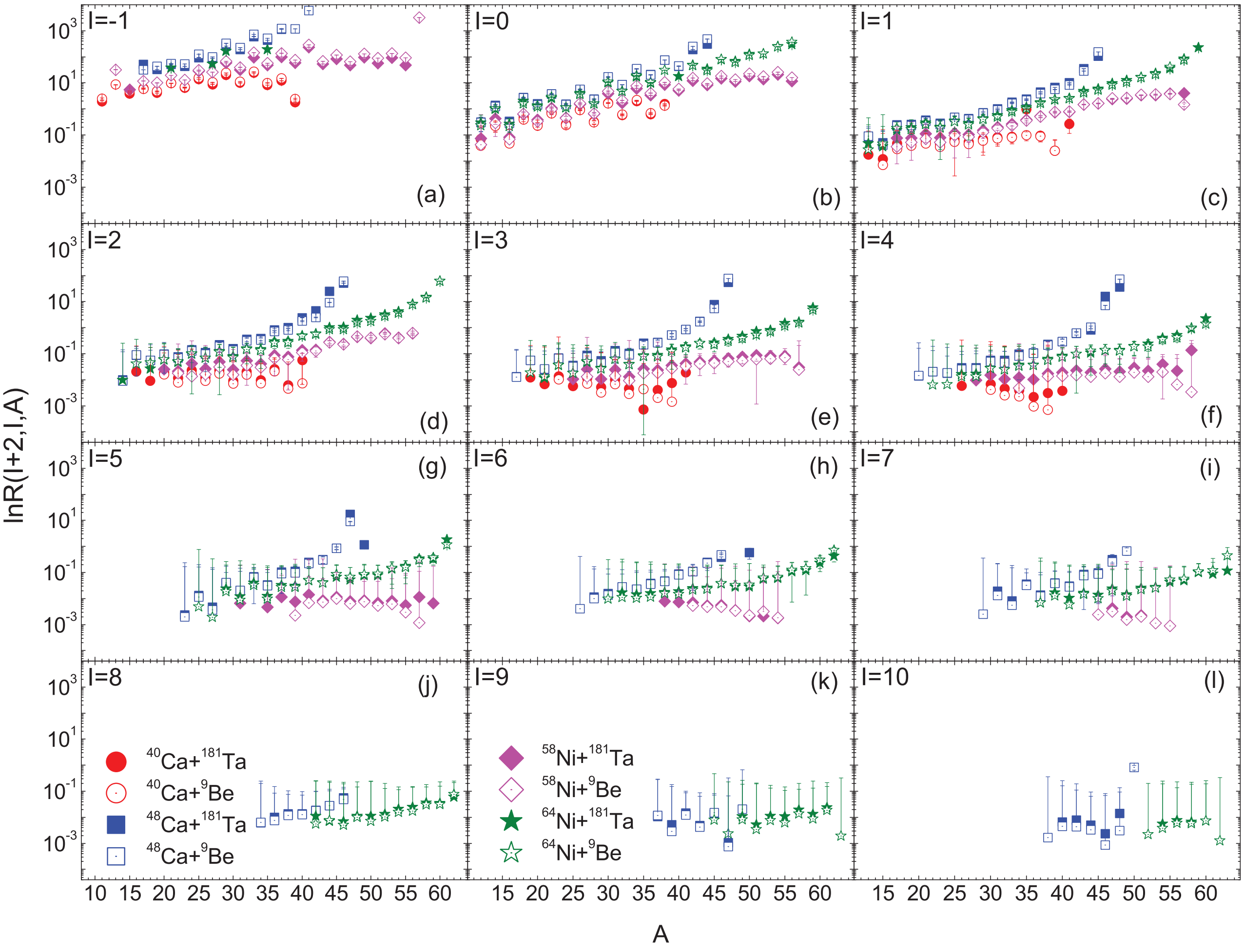

FIG. 1. (Color online) The IYR for fragments produced in the 140*A* MeV ^{48,40}Ca + ^{181}Ta/^{9}Be and ^{58,64}Ni + ^{181}Ta/^{9}Be reactions [22]. The solid and open symbols denote the IYR for the fragments in the reactions with the ^{181}Ta and ^{9}Be targets, respectively.

two reactions, which is correlated to the relative neutron (proton) density between the reactions in the form of $e^{\alpha} = \hat{\rho}_n = \frac{\rho_{n,2}}{\rho_{n,1}}$ ($e^{\beta} = \hat{\rho}_p = \frac{\rho_{p,2}}{\rho_{p,1}}$) or equivalently $\alpha = \ln\rho_{n,2} - \ln\rho_{n,1}$ ($\beta = \ln\rho_{p,2} - \ln\rho_{p,1}$) [5,13,34,35]. The relationship $\Delta\mu/T = \alpha - \beta$ has been verified in the measured yields of fragments and the calculated data of the antisymmetric molecular dynamical model [2,3].

III. RESULTS AND DISCUSSION

First, we study the target effects in the IYR, $\ln R(I+2, I, A)$, for the fragments produced in the 140*A* MeV ^{48,40}Ca + ^{181}Ta/^{9}Be and ^{58,64}Ni + ^{181}Ta/^{9}Be reactions by using the NSCL data. The IYRs are plotted in Fig. 1. In brief, we roughly divide the fragments into three groups according to mass, i.e., the small-*A*, the intermediate-*A*, and the large-*A* fragments (the mass ranges of the fragments are not specified since they vary in different *I* chains). In reactions with the same projectile, the IYR for fragments with the ^{181}Ta target is relatively larger than that of the ^{9}Be target (except for the $I = -1$ fragments). But in general the difference between the IYRs for reactions with the ^{181}Ta and ^{9}Be targets is small, and larger differences appear in the neutron-rich fragments or the large-*A* fragments in some *I* chains. For example, large differences only occur in the IYRs for the $I = 8$, 9, and 10 fragment chains in the ^{64}Ni + ^{181}Ta/^{9}Be reactions, in the IYRs for the $I = 9$ and 10 fragment chains in the ^{48}Ca + ^{181}Ta/^{9}Be reactions, or in the large-*A* fragments of the $I = 3$ and 4 fragment chains in the ^{40}Ca + ^{181}Ta/^{9}Be reactions. The IYRs in the ^{48}Ca and ^{64}Ni reactions are less influenced by the targets compared to those in the ^{40}Ca and ^{58}Ni reactions. It can only be concluded that the IYR has a small dependence on the target used in the reactions, but the degree of dependence varies in the reactions. Compared to the small-*I* fragments, it is also observed that the IYRs for the large-*I* fragments have relatively large errors.

Second, we study the target effects in the IBD results ($\Delta\mu/T$). For simplification, the $\Delta\mu/T$ obtained from the ^{48}Ca + ^{181}Ta and ^{40}Ca + ^{181}Ta reactions are labeled as C_{11}, the $\Delta\mu/T$ from the ^{48}Ca + ^{9}Be and ^{40}Ca + ^{9}Be reactions as C_{12}, the $\Delta\mu/T$ from the ^{64}Ni + ^{181}Ta and ^{58}Ni + ^{181}Ta reactions as C_{21}, the $\Delta\mu/T$ from the ^{64}Ni + ^{9}Be and ^{58}Ni + ^{9}Be reactions as C_{22}, the $\Delta\mu/T$ from the ^{58}Ni + ^{181}Ta and ^{40}Ca + ^{181}Ta reactions as C_{31}, the $\Delta\mu/T$ from the ^{58}Ni + ^{9}Be and ^{40}Ca + ^{9}Be reactions as C_{32}, the $\Delta\mu/T$ from the ^{48}Ca + ^{181}Ta and ^{64}Ni + ^{181}Ta reactions as C_{41}, and the $\Delta\mu/T$ from the

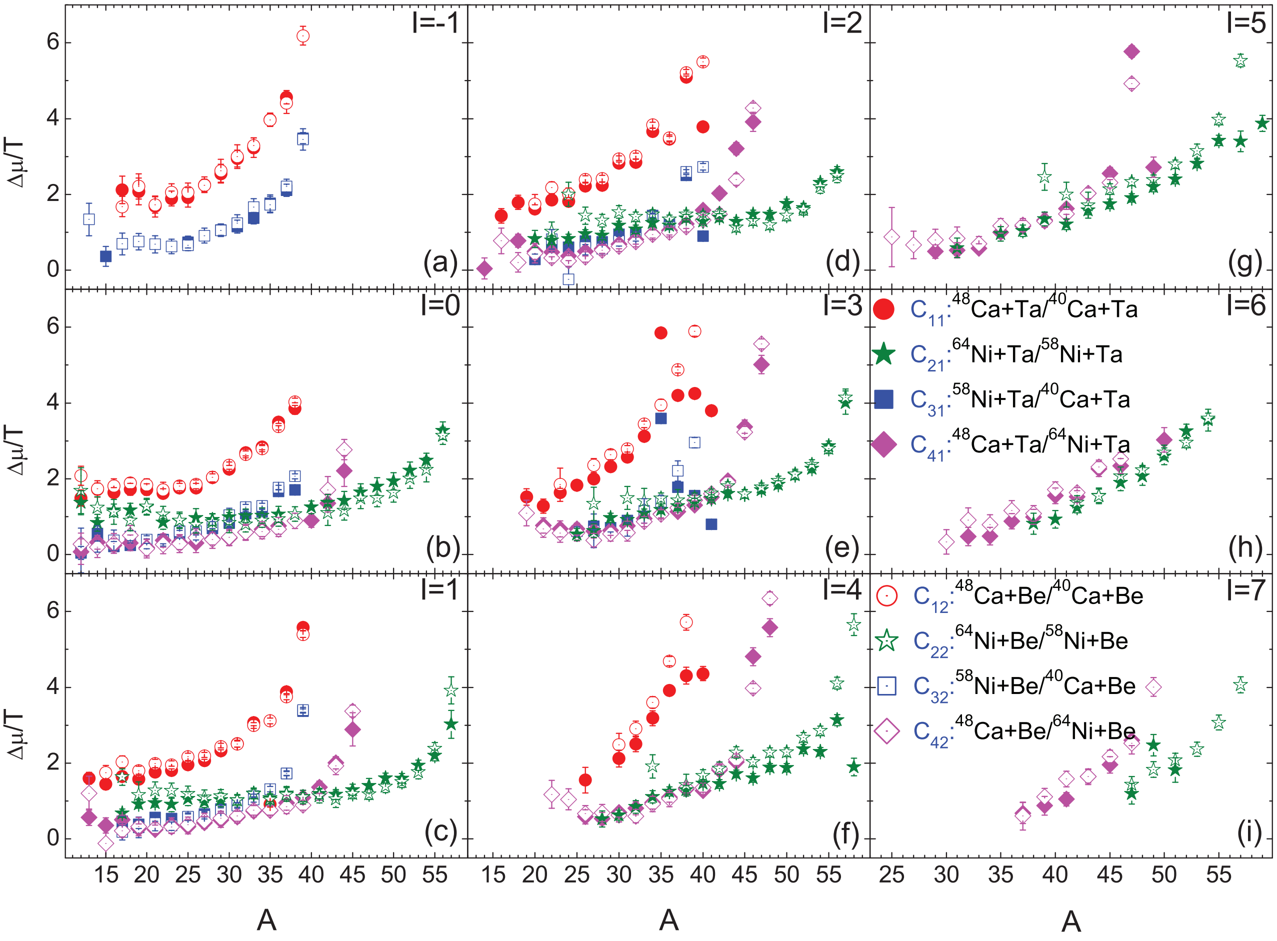

FIG. 2. (Color online) The IBD results for the measured reactions induced by ^{40,48}Ca and ^{58,64}Ni in the target nuclei ^{181}Ta and ^{9}Be. The solid and open symbols denote the IBDs for the two reactions with the target nuclei ^{181}Ta and ^{9}Be, respectively. In the labels C_{ij} (see the text for explanations), i denotes the pair of reactions used to extract the IBD results, and $j = 1$ or 2 denotes the reaction with the targets ^{181}Ta and ^{9}Be, respectively.

^{48}Ca + ^{9}Be and ^{64}Ni + ^{9}Be reactions as C$_{42}$. The IBD results for the fragment with $I = -1$ to 7 are plotted in Fig. 2. For most of the fragments, the errors of the obtained $\Delta\mu/T$ are very small. In general, the differences between C$_{i1}$ and C$_{i2}$ are small except for some fragments. The differences between C$_{11}$ and C$_{12}$ are small for the $I = -1$ and 1 fragments. A small difference between C$_{11}$ and C$_{12}$ is found in the small-A fragments of the $I = 1$ fragments, and a larger difference between C$_{11}$ and C$_{12}$ is shown in all fragments of the $I = 2$ and 3 fragment chains. Moreover, a much larger difference between C$_{12}$ and C$_{11}$ is found in the large-A fragments compared to those in the small-A fragments of the $I > 2$ chains. The similar distributions of C$_{12}$ and C$_{11}$ are also found in C$_{21}$ and C$_{22}$. In the $I = 1$ and 2 fragment chains, C$_{22}$ is found to be larger than C$_{21}$ in the small-A fragments, C$_{22}$ approximates C$_{21}$ in the intermediate-A fragments, and C$_{22}$ is smaller than C$_{21}$ in the large-A fragments. For the $I = 4$ and 5 fragment chains, C$_{22}$ is larger than C$_{21}$. This phenomena is similar to that of C$_{12}$ and C$_{11}$. For the reactions of the symmetric ^{58}Ni and ^{40}Ca projectiles, C$_{31}$ and C$_{32}$ for most of the fragments are similar except for the large-A fragments in the $I = 3$ chains. For the reactions of the asymmetric ^{48}Ca and ^{64}Ni projectiles, C$_{41}$ and C$_{42}$ also are similar for most of the fragments when $I \leqslant 4$. A relatively large difference between C$_{42}$ and C$_{41}$ is found in the $I > 4$ fragment chains, in which C$_{42} >$ C$_{41}$. In addition, large differences between C$_{42}$ and C$_{41}$ can be found in the large-A fragments in all the I chains. It is concluded that, for reactions with the same projectile but different target nuclei, the IBD results depend on the asymmetry of the targets to different degrees.

To quantitatively show the target effects in the IBD results, a ratio ($r_{\Delta\mu}$) between the IBD results is defined, i.e., $r_{\Delta\mu} = C_{i1}/C_{i2}$, with 1 and 2 denoting the reactions by using the Ta and Be targets, respectively. With different excitation energies, the temperatures are found to be different in the various reactions [36]. In the IBD probe, the excitation energies of the isobaric fragments are sorted to the free energies, which cancel out in the calculation of $\Delta\mu/T$ [2,4,5]. Moreover, it has been proven that, except for some fragments, the temperatures of the fragments produced in the 140A MeV ^{48}Ca + ^{9}Be/^{181}Ta or ^{64}Ni + ^{9}Be/^{181}Ta reactions are almost the same by using the isotopic thermometer [26]. It is reasonable to assume the

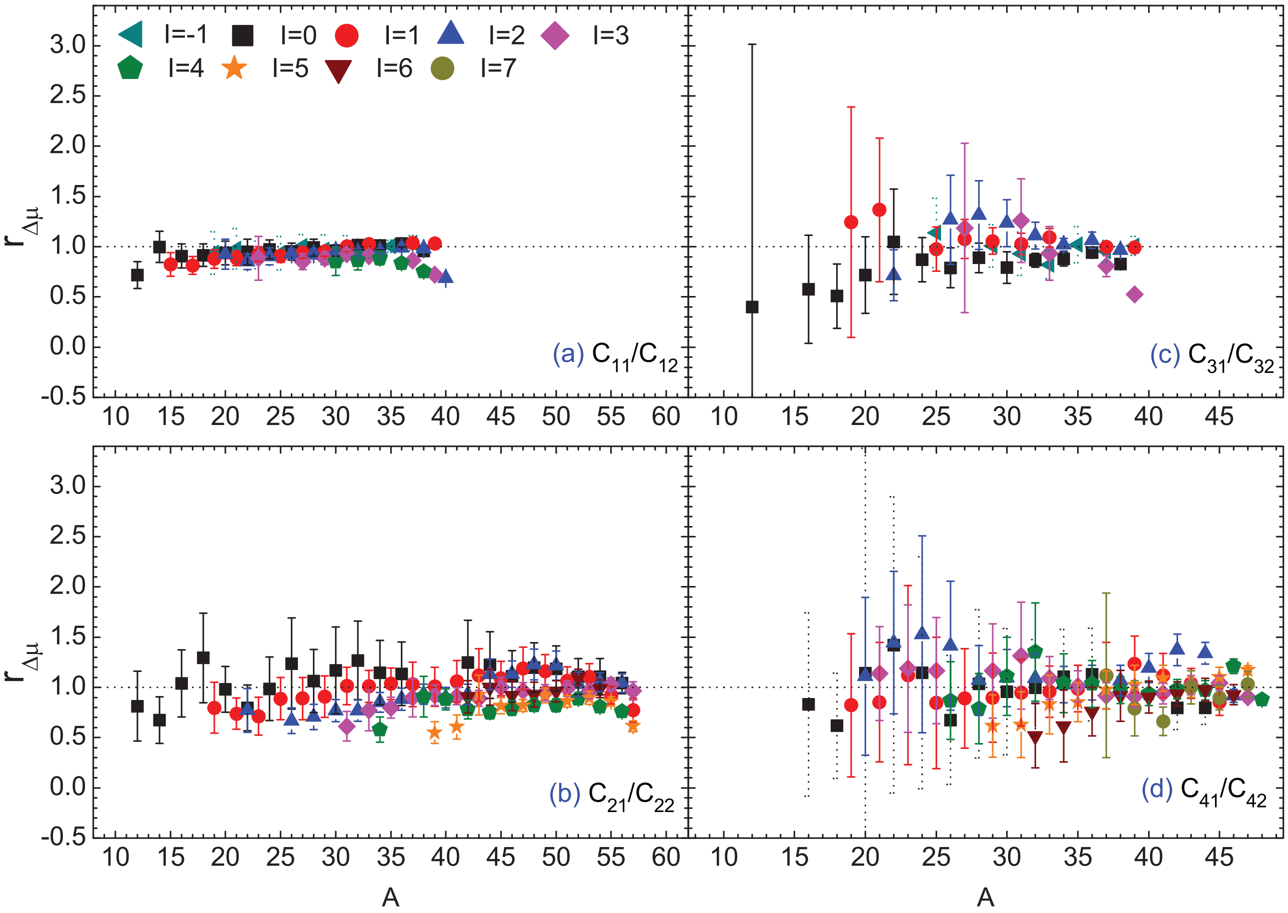

FIG. 3. (Color online) The ratio ($r_{\Delta\mu}$) between the IBD results for reactions with the target nuclei ^{181}Ta and ^{9}Be. (a) The ratio for $r_{\Delta\mu} = \mathrm{C}_{11}/\mathrm{C}_{12}$. (b) The ratio for $r_{\Delta\mu} = \mathrm{C}_{21}/\mathrm{C}_{22}$. (c) The ratio for $r_{\Delta\mu} = \mathrm{C}_{31}/\mathrm{C}_{32}$. (d) The ratio for $r_{\Delta\mu} = \mathrm{C}_{41}/\mathrm{C}_{42}$. See the text for the explanations of C_{ij}.

temperatures of fragments produced in the reactions with Be and Ta targets are the same. By defining $r_{\Delta\mu}$, the T dependence of $\Delta\mu/T$ in Eq. (3) is removed in $r_{\Delta\mu}$, and $r_{\Delta\mu}$ only reflects the ratio of the chemical difference between neutrons and protons of the reactions, i.e., $r_{\Delta\mu} = \Delta\mu_{Ta}/\Delta\mu_{Be}$. It has been noted that $\Delta\mu/T$ is related to the density difference between the reactions, which is $\Delta\mu/T = \ln\rho_{n2} - \ln\rho_{n1} - (\ln\rho_{p2} - \ln\rho_{p1})$ [5]. The values of $r_{\Delta\mu}$ for the four compared groups are plotted in Fig. 3. For $\mathrm{C}_{11}/\mathrm{C}_{12}$ as plotted in Fig. 3(a), most of the values of $r_{\Delta\mu}$ are between 0.8 and 1.05, and $r_{\Delta\mu}$ for fragments with different I only have small differences, indicating the generally suppressed $\Delta\mu$ by using the heavy Ta target. The errors of $r_{\Delta\mu}$ for $\mathrm{C}_{11}/\mathrm{C}_{12}$ are very small. In Fig. 3(b), $r_{\Delta\mu}$ for $\mathrm{C}_{21}/\mathrm{C}_{22}$ are within a relatively large range from 0.3 to 1.3, with $r_{\Delta\mu}$ decreasing as I increases. Besides the $r_{\Delta\mu}$ for the $I = 0$ and 1 isobaric chains, the values for $r_{\Delta\mu}$ are similar. The errors of $r_{\Delta\mu}$ for $\mathrm{C}_{21}/\mathrm{C}_{22}$ are larger than those for $\mathrm{C}_{11}/\mathrm{C}_{12}$. In Fig. 3(c), for which the projectile nuclei are both symmetric, the values of $r_{\Delta\mu}$ approximate to 1, but $r_{\Delta\mu}$ increases with I in the $I = 1$, 2, and 3 fragments. In Fig. 3(d), for reactions with projectiles that are both neutron-rich, most of the values of $r_{\Delta\mu}$ are similar, in the range from 0.6 to 1.4, and no obvious dependence of $r_{\Delta\mu}$ on I is found. For the $I = 0$, 1, and 2 fragments, the errors of $r_{\Delta\mu}$ for $\mathrm{C}_{31}/\mathrm{C}_{32}$ and $\mathrm{C}_{41}/\mathrm{C}_{42}$ are very large. The values of $r_{\Delta\mu}$ for the four reaction groups quantitatively show the dependence of the IBD results on the targets, which changes with the asymmetry of the reaction system.

Though $r_{\Delta\mu}$ depends on the I of fragments to different degrees, $r_{\Delta\mu}$ is found to depend on A of the $I = 1$ fragment only slightly in all the studied reactions. The values of $r_{\Delta\mu}$ for the $I = 1$ fragments are compared in Fig. 4. Relatively consistent $r_{\Delta\mu}$ values are found except for some of the fragments. In Fig. 2(c), the plateaus of $\Delta\mu/T$ for the $I = 1$ isobaric chain change very slightly and can well indicate the difference among the IBD results for the reactions with different projectiles. From the results of $r_{\Delta\mu}$ and $\Delta\mu/T$, it is suggested that the IBD plateau for the $I = 1$ isobaric chain is a good probe to indicate the difference between the neutron and proton densities of the reaction systems. In addition, to avoid the asymmetry introduced by the target nucleus, it is also proposed that symmetric target nuclei should be used in the IBD experiments.

IV. SUMMARY

The IBD result is explained as a probe to study the density difference between the reaction systems. The target effects in the IYR and IBD are investigated by using the measured data in

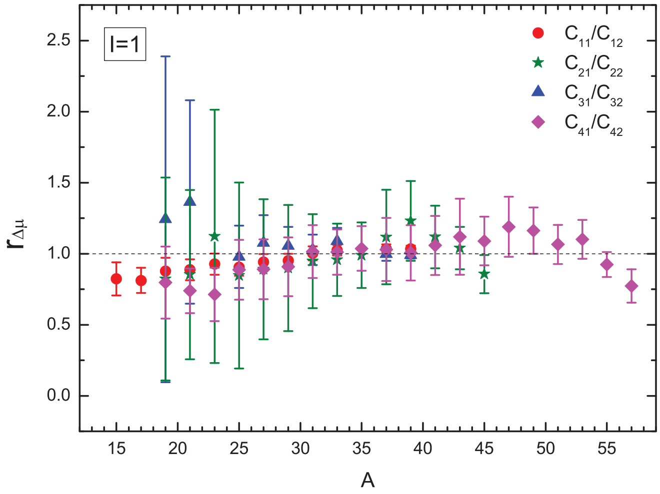

FIG. 4. (Color online) Comparison between the values of $r_{\Delta\mu}$ for the $I = 1$ fragments plotted in Fig. 3.

the 140A MeV ^{40,48}Ca + ^{181}Ta/^{9}Be and ^{58,64}Ni + ^{181}Ta/^{9}Be reactions. The IYRs and IBDs in the four compared groups of reactions are found to depend on the targets to different degrees, and the dependence also varies with the mass and neutron excess of the fragments. By defining the ratio between the IBD results for the reactions with Be and Ta targets, it is found that the IBD results are generally suppressed by using the ^{181}Ta target. The IBD results for the $I = 1$ isobaric chain are suggested to be a good probe to study the difference between the neutron and proton densities of the reaction systems.

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[1] B.-A. Li, L.-W. Chen, and C. M. Ko, Phys. Rep. **464**, 113 (2008).
[2] C. W. Ma, S. S. Wang, Y. L. Zhang, and H. L. Wei, Phys. Rev. C **87**, 034618 (2013).
[3] C. W. Ma, S. S. Wang, Y. L. Zhang, and H. L. Wei, J. Phys. G: Nucl. Part. Phys. **40**, 125106 (2013).
[4] C. W. Ma, J. Yu, X. M. Bai, Y. L. Zhang, H. L. Wei, and S. S. Wang, Phys. Rev. C **89**, 057602 (2014).
[5] C.-W. Ma, X.-M. Bai, J. Yu, and H.-L. Wei, Eur. Phys. J. A **50**, 139 (2014).
[6] M. Huang, Z. Chen, S. Kowalski *et al.*, Phys. Rev. C **81**, 044620 (2010).
[7] P. Marini, A. Bonasera, A. McIntosh *et al.*, Phys. Rev. C **85**, 034617 (2012).
[8] C. W. Ma, F. Wang, Y. G. Ma, and C. Jin, Phys. Rev. C **83**, 064620 (2011).
[9] C.-W. Ma, J. Pu, H.-L. Wei *et al.*, Eur. Phys. J. A **48**, 78 (2012).
[10] M. Huang, A. Bonasera, Z. Chen *et al.*, Phys. Rev. C **81**, 044618 (2010).
[11] H. S. Xu *et al.*, Phys. Rev. Lett. **85**, 716 (2000).
[12] Y. G. Ma *et al.*, Phys. Rev. C **69**, 064610 (2004); **72**, 064603 (2005).
[13] M. B. Tsang, W. A. Friedman, C. K. Gelbke, W. G. Lynch, G. Verde, and H. Xu, Phys. Rev. Lett. **86**, 5023 (2001).
[14] G. A. Souliotis, D. V. Shetty, A. Keksis, E. Bell, M. Jandel, M. Veselsky, and S. J. Yennello, Phys. Rev. C **73**, 024606 (2006).
[15] C. W. Ma, H. L. Wei, J. Y. Wang *et al.*, Phys. Rev. C **79**, 034606 (2009).
[16] C. W. Ma, H. L. Wei, and J. Y. Wang, Chin. Phys. B **18**, 4781 (2009).
[17] D. Q. Fang, W. Q. Shen, J. Feng *et al.*, Phys. Rev. C **61**, 044610 (2000).
[18] D. Q. Fang, W. Q. Shen, J. Feng *et al.*, Chin. Phys. Lett. **17**, 267 (2000).
[19] C.-W. Ma, H.-L. Wei, H.-Y. Wang, W.-F. Li, and Y.-Q. Li, Nucl. Phys. A **834**, 581c (2010).
[20] C. Ma, Y. Zhang, and C. Jin, Plasma Sci. Technol. **14**, 396 (2012).
[21] C. W. Ma, H. L. Wei, G. J. Liu, and J. Y. Wang, J. Phys. G: Nucl. Part. Phys. **37**, 015104 (2010).
[22] M. Mocko *et al.*, Phys. Rev. C **74**, 054612 (2006).
[23] C. W. Ma, J. Pu, Y. G. Ma, R. Wada, and S. S. Wang, Phys. Rev. C **86**, 054611 (2012).
[24] C. W. Ma, X. L. Zhao, J. Pu *et al.*, Phys. Rev. C **88**, 014609 (2013).
[25] H. L. Wei and C. W. Ma, Acta Phys. Sin. **59**, 5364 (2010) (in Chinese).
[26] C. W. Ma *et al.*, Commun. Theor. Phys. **59**, 95 (2013).
[27] Y. Fu *et al.*, Chin. Phys. Lett. **26**, 082503 (2009).
[28] M. Mocko, M. B. Tsang, D. Lacroix, A. Ono, P. Danielewicz, W. G. Lynch, and R. J. Charity, Phys. Rev. C **78**, 024612 (2008).
[29] C. W. Ma, S. S. Wang, H. L. Wei, and Y. G. Ma, Chin. Phys. Lett. **30**, 052101 (2013).
[30] C. W. Ma, H. L. Wei, and Y. G. Ma, Phys. Rev. C **88**, 044612 (2013).
[31] C. B. Das, S. Das Gupta, X. D. Liu, and M. B. Tsang, Phys. Rev. C **64**, 044608 (2001).
[32] M. B. Tsang, W. G. Lynch, W. A. Friedman *et al.*, Phys. Rev. C **76**, 041302(R) (2007).
[33] A. S. Hirsch, A. Bujak, J. E. Finn *et al.*, Phys. Rev. C **29**, 508 (1984).
[34] A. S. Botvina, O. V. Lozhkin, and W. Trautmann, Phys. Rev. C **65**, 044610 (2002).
[35] E. Geraci, M. Bruno, M. D'Agostino *et al.*, Nucl. Phys. A **732**, 173 (2004).
[36] J. B. Natowitz, R. Wada, K. Hagel *et al.*, Phys. Rev. C **65**, 034618 (2002).