New experimental evidence for universal odd-even staggering in fragmentation cross sections

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About 100 isotopes with $(N - Z)$ from 1–9 produced by 300 MeV/nucleon ^{78}Kr projectiles impinging on an Al_2O_3 target have been separated and identified at the RIBLL2 separator of HIRFL, where their production yields have been measured. The odd-even staggering (OES) in these experimental yields is quantitatively studied by employing a third-order difference formula. Measured data are used to validate the universality of this OES by comparing with other experimental data produced by fragmentation of different krypton projectiles on various targets as well as the OES evaluated from thousands of accurate cross sections measured in many different reactions. These comparisons between experimental data from a large variety of fragmentation reactions provide strong evidence that the OES magnitude almost does not depend on the projectile-target combinations and thus the OES is universal for different reaction systems. The OES magnitudes in these experimental data are also applied to examine the OES predicted by the abrasion-ablation model. There are large discrepancies between the OES magnitudes in predicted and measured cross sections.

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I. INTRODUCTION

Many experiments at nuclear physics facilities around the world prove that fragmentation reactions from tens of MeV/nucleon to several GeV/nucleon are very suitable for producing exotic nuclei away from stability. Extensive cross sections of exotic nuclei produced by various fragmentation reactions have been measured at the A1900 separator at MSU [1–4], the Fragment Separator (FRS) at GSI [5–9], the BigRIPS separator at RIKEN [10–14], and the HIRFL-CSR facility at IMP [15–18]. At next generation radioactive beam facilities, e.g., FAIR at GSI [19], FRIB at MSU [20], and HIAF at IMP [21], projectile fragmentation is still one of the most important experimental methods used to study isotopes close to the drip lines. Accurate fragmentation cross sections are required for planning and development of nuclear physics experiments in these facilities. Last, but not least, isotopic cross sections in fragmentation reactions are sensitive parameters for simulations of cosmic-ray propagation in the galaxy, radiation protection in space [22], and cancer therapy using heavy ions [23].

Some fragmentation experiments indicate that the production yields or cross sections of even-Z fragments are systematically higher than those of neighboring odd-Z ones, the so-called odd-even staggering (OES). This OES effect has been noticed in different fragmentation reactions over a wide energy range (see, e.g., Refs. [16,17,24–46]). However, quantitative and accurate investigations of the OES in most of these experimental data are lacking, especially for nuclei away from stability. This is caused by the large uncertainties in many measured data and difficulties in full A and Z identification in previous experiments. In recent works [16,17], the OES has been quantitatively studied by using production yields of some neutron-deficient nuclei accurately measured in a heavy-ion storage ring at IMP [15]. These OES studies for the neutron-deficient nuclei produced by several fragmentation reactions tend to imply that this OES is almost universal for their cross sections measured in different fragmentation reaction systems [16,17]. More recently, further OES investigations have been performed for many neutron-rich nuclei [47,48], where the OES magnitudes in around 5000 experimental cross sections from various reaction systems at different energies have been compared. These comparisons indicate that this OES is nearly independent of the projectile-target combinations and the projectile energy. This universal OES in measured cross sections seems to be related to the OES in the particle-emission threshold energies of excited nuclei during the final evaporation phase [16,17,33,49]. To further examine the universality of the OES in more isotopic cross sections, new experimental data from different fragmentation reactions with various projectile-target combinations are particularly welcome.

Different fragmentation models have been employed to predict isotopic cross sections. First, some empirical models, such as the parametrization EPAX3 without OES [50] and the improved FRACS with OES [51], have been developed for fast calculations of fragmentation cross sections. Second, different Monte Carlo models, e.g., the abrasion-ablation model

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[49] and the isospin-dependent quantum molecular dynamics model combined with the statistical decay code GEMINI [39], are also widely used for fragmentation reactions. However, some studies indicate that it is difficult for these models to reproduce the OES in measured cross sections of extensive fragments over a large range of Z and N, especially for those far away from stability; see Refs. [16,17,33,45,48] for details. More recently, four simple OES relations based on the universality of the OES in isotopic cross sections have been proposed for accurate interpolation or extrapolation of fragmentation cross sections [52,53]. These OES relations can be used to provide reliable cross sections for experiments aimed at measuring new isotopes approaching the drip lines. The OES in cross sections predicted by various theoretical methods should be validated with more experimental data to improve their calculations for isotopic cross sections in fragmentation reactions.

In this work, yields of many fragments with $(N-Z)$ from 1–9 produced by 300 MeV/nucleon ^{78}Kr projectiles on an Al_2O_3 target are obtained from one fragmentation experiment at in-flight fragment separator RIBLL2 at IMP. Magnitudes of the OES in these measured yields are derived by using a third-order difference equation. Furthermore, these OES magnitudes are also compared with those in other experimental data produced by fragmentation reactions of different krypton (^{78,84,86}Kr) projectiles on various targets as well as the OES evaluated from extensive cross sections measured in different reaction systems. At last, OES magnitudes in these experimental data are used to check the OES in cross sections predicted by the abrasion-ablation model (ABRABLA07) [49].

II. EXPERIMENT AND DATA ANALYSIS

This experiment was performed at the RIBLL2 separator at the Heavy-Ion Research Facility in Lanzhou (HIRFL), where some nucleon-knockout reactions of light nuclei were also studied recently [54–56]. The primary beam of ^{78}Kr was accelerated to 300 MeV/nucleon by the main Cooler Storage Ring (CSRm). After this, these ^{78}Kr projectiles were delivered to RIBLL2 and focused on an Al_2O_3 target with a thickness of 1.84 mm placed at the entrance of RIBLL2. Fragments emerged from this Al_2O_3 target as fully stripped nuclei at the energy of 300 MeV/nucleon. The magnetic rigidity $B\rho$ of the RIBLL2 separator was set to around 5.44 Tm, and the horizontal slits at the F1 were fully opened. Many fragments with Z from 5–33 produced by ^{78}Kr fragmentation were transported to the External Target Facility (ETF) and identified with the $B\rho$-ToF-ΔE technique, as reported in Ref. [57]. The particle energy loss (ΔE) was measured with a multiple sampling ionization chamber (MUSIC) at the ETF [58]. The time of flight (ToF) was determined by plastic scintillator detectors, which were installed at the F1 and the ETF with a flight path of 26 m. The precise $B\rho$ determination was achieved by means of trajectory reconstruction, in which the measured particle trajectories were combined with ion-optical transfer matrix elements deduced from experimental data. More details about the experimental setup and the particle identification scheme can be found in Ref. [57].

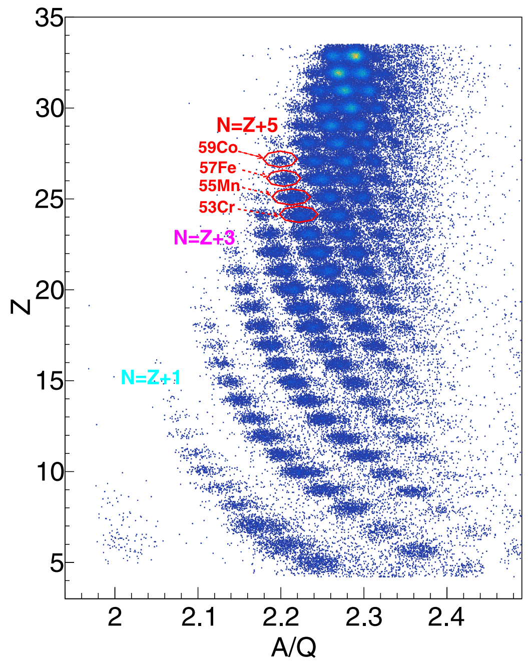

FIG. 1. Particle identification spectrum of the atomic number Z versus the mass-to-charge ratio A/Q for isotopes produced by the 300 MeV/nucleon ^{78}Kr +Al_2O_3 reaction. Produced isotopes with $(N-Z)$ from 1–9 can be identified clearly in this experiment. As an example, four neighboring isotopes with $N-Z=5$, namely, ^{59}Co, ^{57}Fe, ^{55}Mn, and ^{53}Cr, are indicated by red ellipses.

The particle identification (PID) plot of many fragments measured in this experiment is shown in Fig. 1. One can see that more than 100 isotopes with $(N-Z)$ from 1–9, produced by fragmentation of ^{78}Kr projectiles, can be separated and identified clearly at the RIBLL2-ETF under full momentum acceptance of about $\pm 4\%$. An atomic number Z resolution of roughly 0.2 charge units (RMS) has been achieved for fragments with Z from 5–33 measured in this experiment.

For the above fragments with $(N-Z)$ from 1–9 measured in this work, their momentum distributions and transmission efficiencies were estimated by a method similar to that used in our previous works [16,17]. Their transmission efficiencies were calculated by employing the LISE++ program [59]. According to our LISE++ calculations, their transmission efficiencies vary almost smoothly with Z along a chain of nuclides with a constant isospin $T_z=(N-Z)/2$. For instance, efficiency values of fragments with $N-Z=4$ are indicated in Fig. 2. This smooth variation of efficiencies is also consistent with results in our previous investigations [16,17]. Thus, corrections with these transmission efficiencies have almost no impact on the OES studies.

One can obtain the production yields of fragments measured in this work, after the number of detected ions has been corrected by their transmission efficiencies. The production yields of measured fragments with $(N-Z)$ from 1–9 are given in Fig. 2. A very evident OES is presented in measured yields of some fragments, e.g., light ones with $N-Z=1$, 2, 3, and 4. For even-mass fragments with $N-Z=2$ and 4, an enhancement in production yields of even-Z ones compared

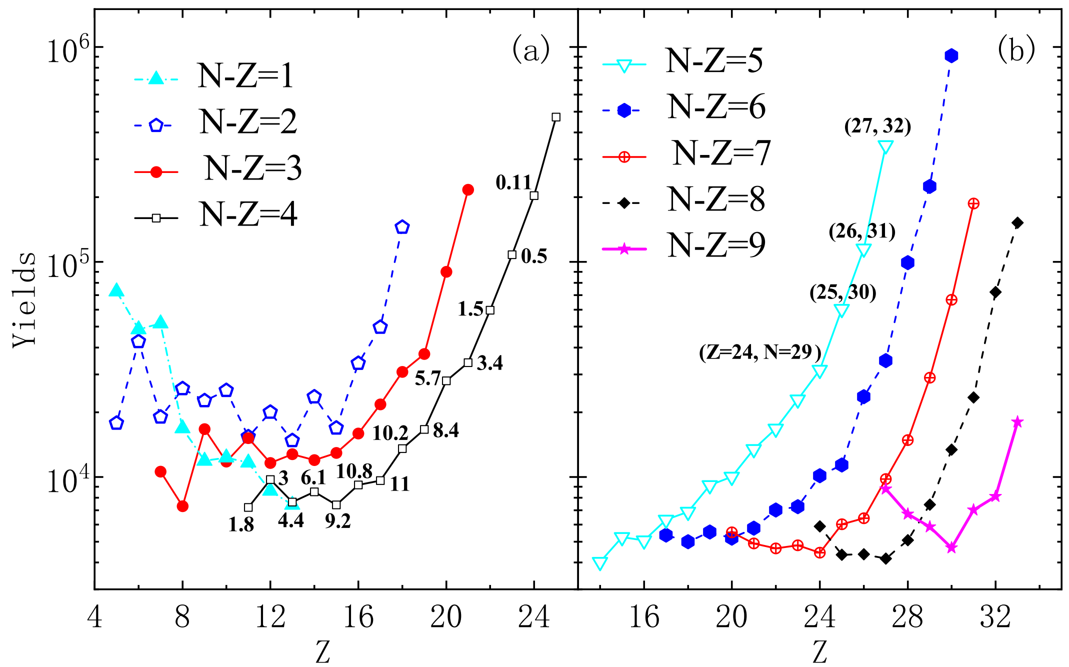

FIG. 2. Production yields of many fragments with $(N-Z)$ from 1–9 measured in this experiment, where the transmission efficiencies have been corrected by LISE++ calculations. Example values of transmission efficiencies (%) are provided for fragments with $N-Z=4$. The proton and neutron numbers are indicated for four neighboring isotopes with $N-Z=5$, namely, ^{53}Cr, ^{55}Mn, ^{57}Fe, and ^{59}Co, and their yields will be used to extract the OES magnitude. The relative error of about 10% is dominated by the systematic uncertainty of the estimations of transmission efficiencies.

to those of odd-Z ones is observed. On the other side, production yields of odd-Z nuclei are enhanced for light odd-mass fragments with $N-Z=1$ and 3. In the following, the OES magnitudes in fragment yields measured in this experiment will be quantitatively investigated and compared with those in some other experimental data as well as OES evaluations from extensive accurate experimental data. Finally, the OES in cross sections calculated with an abrasion-ablation model will also be benchmarked with these experimental data.

III. ODD-EVEN STAGGERING IN EXPERIMENTAL DATA AND MODEL CALCULATIONS

For four neighboring fragments along a constant $T_z = (N-Z)/2$ chain, the OES magnitude in their production yields (cross sections) can be extracted by employing a third-order difference formula [16,17,47,48]:

$$D_{\rm CS}(Z,N) = \tfrac{1}{8}(-1)^{Z+1}\{\ln Y(Z+3,N+3) - \ln Y(Z,N) - 3[\ln Y(Z+2,N+2) - \ln Y(Z+1,N+1)]\}. \quad (1)$$

$Y(Z,N)$ is the production yield (cross section) of a specific nucleus with a proton number Z and a neutron number $N = Z + 2T_z$. For example, yields of four neighboring fragments ^{53}Cr, ^{55}Mn, ^{57}Fe, and ^{59}Co with $N-Z=5$ given in Fig. 2 can be applied to derive the $D_{\rm CS}$ by using this formula. Positive and negative values of $D_{\rm CS}$ indicate enhanced productions of even-Z and odd-Z nuclei, respectively. The absolute value of $D_{\rm CS}$ displays the strength of the OES.

Figure 3 presents the OES magnitudes $D_{\rm CS}$ calculated by Eq. (1) using production yields of many fragments with $(N-Z)$ from 1–9 measured in this experiment. The OES magnitudes from our new experimental data are compared with those evaluated from the average of OES values in thousands of accurate cross sections measured in about 30 different reaction systems at energies between a few tens of MeV/nucleon and a few GeV/nucleon; see Ref. [47] for details. According to their comparisons in Fig. 3, the OES magnitudes ($D_{\rm CS}$) in our experimental data agree very well with those evaluated in Ref. [47], and they show the same evolution tendency along a constant $T_z = (N-Z)/2$ chain.

For light odd-mass fragments (with $N-Z=1$, 3, 5, 7, and 9), a negative $D_{\rm CS}$, namely, a reversed OES, is observed, and it is increased to a small positive value around 0 as Z increases, as shown in Fig. 3. Production yields (cross sections) of these light odd-mass nuclei show a reversed OES, since they predominantly emit neutrons in the evaporation phase and their neutron separation energies are larger for odd-Z fragments with even-N than even-Z ones with odd-N [16]. For even-mass nuclei (with $N-Z=2$, 4, 6, and 8), $D_{\rm CS}$ decreases rapidly from a positive value to about 0 when Z increases. The large positive $D_{\rm CS}$ for light even-mass nuclei originates from a larger neutron separation energy of even-Z fragments with even-N compared to that of odd-Z fragments with odd-N.

For comparison, the OES magnitudes in additional cross sections produced by fragmentation of several krypton projectiles on various targets at different energies, i.e., 483 MeV/nucleon ^{78}Kr+Be [16], 35 MeV/nucleon

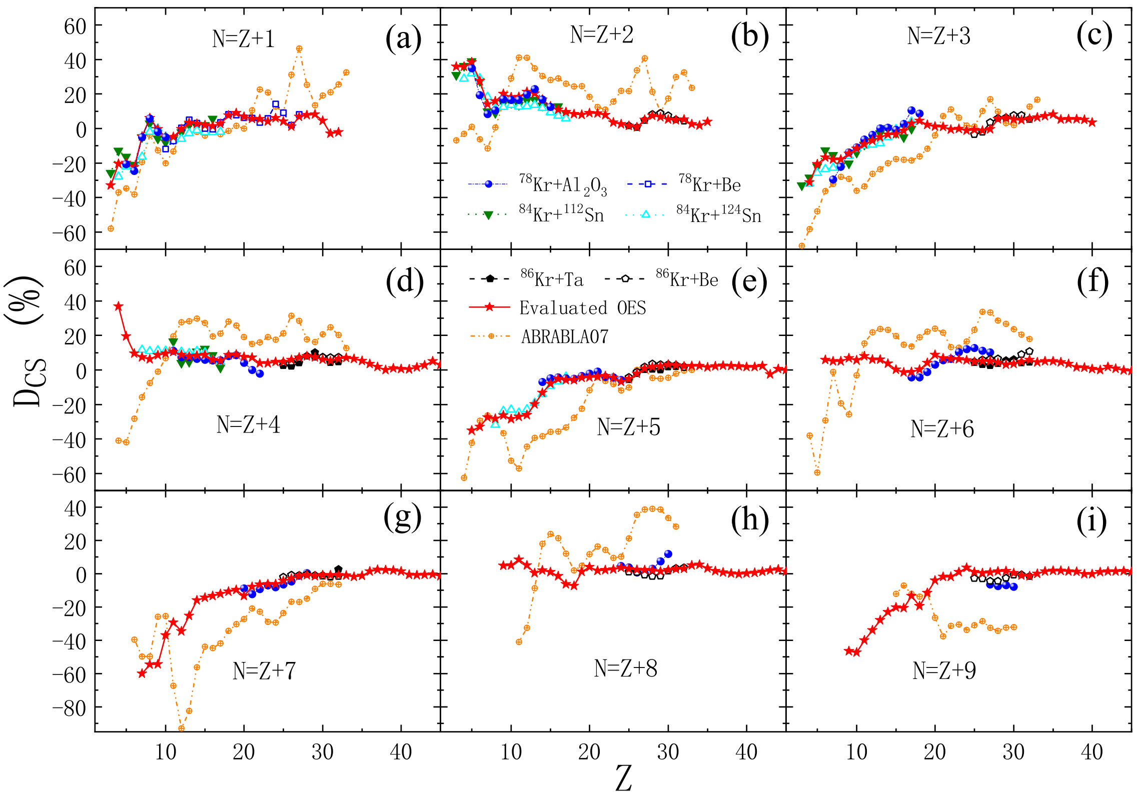

FIG. 3. The OES magnitudes obtained from experimental data of different reactions, i.e., 300 MeV/nucleon ^{78}Kr + Al_2O_3, 483 MeV/nucleon ^{78}Kr + Be [16], 35 MeV/nucleon ^{84}Kr + ^{112,124}Sn [46], and 64 MeV/nucleon ^{86}Kr + Be/Ta [60]. The evaluated OES magnitudes (red stars) are obtained from the weighted average of OES values in extensive measured cross sections [47]. For clarity, the absolute error (around 8% in most cases) for D_{CS} is not shown, which can be calculated on the basis of Eq. (1) by using the relative error of experimental data. The data are shown from (a) $N-Z=1$ to (i) $N-Z=9$. For comparison, the OES magnitudes in cross sections calculated by the ABRABLA07 code [49] using the default parameters are also shown.

^{84}Kr + ^{112,124}Sn [46], and 64 MeV/nucleon ^{86}Kr + Be/Ta [60], are also derived from Eq. (1). As illustrated in Fig. 3, these OES magnitudes in experimental data measured in fragmentation of different krypton projectiles are in very good agreement with D_{CS} in our experimental data as well as those evaluated in Ref. [47]. It should be emphasized that our new experimental data from 300 MeV/nucleon ^{78}Kr + Al_2O_3 and more than 100 experimental data from 35 MeV/nucleon ^{84}Kr + ^{112,124}Sn [46] are not used in the evaluated OES magnitudes from Ref. [47]. The excellent agreement between D_{CS} in these experimental data from ^{78}Kr + Al_2O_3 as well as ^{84}Kr + ^{112,124}Sn and the OES evaluations from previous accurate cross sections provides new experimental evidence for that the OES is independent of the projectile-target combinations as well as the projectile energy and thus it is almost universal for various reaction systems at different energies.

Previous studies suggest that fragmentation models or formulas have difficulties in reproducing the OES in experimental data over a wide range of Z [16,17,48]. D_{CS} values from the above experimental data are also used to check the OES in calculations from the abrasion-ablation model. The OES magnitudes in the above experimental data are compared with those in ^{78}Kr fragmentation cross sections calculated by the abrasion-ablation model ABRABLA07 [49] using the default parameters. For fragments with $N-Z=1$, their OES magnitudes predicted by ABRABLA07 seem to be close to those in experimental data. However, large discrepancies between them are observed for many other fragments, as displayed in Fig. 3. In particular, large negative D_{CS} values for light even-mass nuclei (with $N-Z=2$, 4, 6, and 8) predicted by ABRABLA07 are contradictory to the OES shown in experimental data. These discrepancies may be caused by the parameters used in the final evaporation phase of model. Predictions from fragmentation models should be checked and improved by using more accurate experimental data, especially for fragments close to the drip lines.

The above studies in this work demonstrate that the OES magnitudes in production cross sections of fragments with $(N-Z)$ from 1–9 are almost universal for fragmentation of different krypton (^{78,84,86}Kr) projectiles on various targets (Al_2O_3, Be, Ta, ^{112,124}Sn). Additionally, these OES magnitudes are also consistent with those evaluated from thousands of accurate cross sections measured in different reaction systems. However, these OES magnitudes in experimental data can hardly be reproduced by the abrasion-ablation model. More experimental cross sections near the drip lines are required for further validating the universality of OES in isotopic cross sections as well as the OES magnitudes predicted by reaction models.

IV. SUMMARY

In summary, production yields of many fragments with $(N - Z)$ from 1–9 produced by ^{78}Kr fragmentation have been measured at the RIBLL2 separator of HIRFL. A third-order difference formula has been applied to extract the OES magnitudes in these measured yields. Large positive and negative values of D_{CS} are observed for light fragments with even-mass and odd-mass, respectively. The OES magnitudes in our experimental data are also compared with those in other experimental data produced by fragmentation of different krypton (^{78,84,86}Kr) projectiles on various targets (Al_2O_3, Be, Ta, ^{112,124}Sn) as well as the OES evaluations from thousands of accurate cross sections measured in about 30 different reaction systems. The good agreement between the OES in these experimental data strongly supports that the OES magnitude is nearly independent of the projectile-target combinations as well as the projectile energy. The abrasion-ablation model (ABRABLA07) seems to be unable to reproduce the OES magnitudes in experimental data, according to their comparisons illustrated in this work. Future OES studies with more experimental data, especially for fragments approaching the drip lines, will be performed to benchmark the universality of the OES in different reactions as well as the OES in cross sections calculated by various fragmentation models. Further studies with various models are also required to understand the reaction mechanism and the origin of the OES.

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