Universal odd-even staggering in isotopic fragmentation and spallation cross sections

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(Received 27 June 2019; revised manuscript received 22 October 2019; published 25 November 2019)

In a recent work [Phys. Rev. C **97**, 044619 (2018)], a universal odd-even staggering (OES) has been observed in isotopic cross sections of neutron-rich nuclei produced by various fragmentation and spallation reactions. However, the universality of this OES is not clear for neutron-deficient nuclei, and thus more quantitative studies of this OES effect are required for these nuclei from different reactions. For neutron-deficient nuclei with $(N - Z)$ from 0 to -4, the OES magnitudes are calculated by a third-order difference formula using cross sections measured in various fragmentation and spallation systems and they are applied to derive the evaluation values of the OES magnitudes. The evaluated OES magnitudes for both neutron- and proton-rich nuclei are benchmarked with some additional experimental data from fragmentation as well as spallation reactions. Furthermore, the OES factors predicted by two recent fragmentation and spallation models are checked by comparing with the OES magnitudes evaluated from extensive experimental data. This comparison suggests that the OES factors in these fragmentation and spallation models should be improved to reproduce measured cross sections.

DOI: 10.1103/PhysRevC.100.054619

I. INTRODUCTION

Fragmentation and spallation reactions are widely used in nuclear physics experiments to produce and study exotic nuclei at most existing [1–12] as well as planned [13–15] radioactive beam facilities. Accurate isotopic spallation cross sections are also key ingredients for reliable simulations of the propagation of cosmic-ray nuclei in the galaxy and calculations of the isotopic composition of the galactic cosmic-ray source [16–18]. Furthermore, a solid knowledge of spallation reactions provides the basis not only for spallation neutron sources [19–22] but also for accelerator-driven subcritical reactor systems [23]. Finally, fragmentation and spallation reactions play an important role in cancer therapy using heavy ions and protons, respectively [24]. Accurate calculations or measurements of fragmentation and spallation cross sections are essential for the design of nuclear physics experiments and other applications mentioned above.

According to many fragmentation and spallation experiments, measured production cross sections (yields) of fragments show an evident odd-even staggering (OES), which means a much higher production of even-Z fragments than the neighboring odd-Z ones (see, e.g., Refs. [8,9,12,25–43]). However, a quantitative and accurate study of this OES in isotopic cross sections was not carried out in most of the above experiments, which was mainly caused by difficulties in full A and Z identification [26,27,30,35,36] as well as very large experimental uncertainties (see, e.g., Refs. [25,34]).

Recently, extensive cross sections of various neutron-rich nuclei have been accurately measured for many different fragmentation and spallation reaction systems with a large variety of projectile-target combinations over a wide energy range [2–5,8,44–49]. With these accurate experimental data, the OES in isotopic cross sections has been systematically investigated for a large number of neutron-rich nuclei with $(N - Z)$ from 1 to 23, where the OES magnitude has been found to be system independent [43]. However, in the case of neutron-deficient nuclei, accurate experimental data are rather few due to their small production cross sections and short half-lives. On the basis of recent experiments with a heavy-ion storage ring [8,9,50], the OES in production yields (cross sections) of some neutron-deficient nuclei has been investigated in only few fragmentation reactions. For neutron-deficient nuclei, it is necessary to quantitatively study this OES in more fragmentation as well as spallation reactions and verify the universality of this OES for different fragmentation and spallation reaction systems.

The OES of fragmentation and spallation cross sections seems to be formed in the evaporation process and originate mainly from the OES of the particle-emission threshold energies of excited nuclei [8,9,34,51]. This threshold energy can be determined from the nucleon separation energies of fragments and is strongly affected by some nuclear structure effects, e.g., pairing [8,9,34,51], closed shell [8,9] and nuclear level density [8,52]. Based on the above conclusions in Refs. [8,9,34,51], the OES in fragment cross sections has been implemented in recent empirical models, i.e., FRACS [53] and SPACS [54], for fragmentation and spallation reactions, respectively. However, the OES factors included in these

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empirical models are from very limited experimental data and should be validated by using more experimental data. According to studies in Refs. [8,9,34,42], it is rather difficult for some Monte Carlo models, e.g., the abrasion-ablation model [51] and the improved statistical multifragmentation model with secondary decay [42], to reproduce the measured OES in isotopic cross sections over a wide range of Z and N. Therefore, more OES studies should be performed to understand the OES of isotopic cross sections measured in different reaction systems, to validate the OES factors used in aforementioned empirical models, and to accurately calculate isotopic cross sections of exotic nuclei produced in various fragmentation and spallation reactions.

In our recent work [43], the OES in cross sections of many neutron-rich nuclei has been found to be a universal quantity for various fragmentation as well as spallation systems and the evaluation value of this OES has been derived from extensive experimental data of neutron-rich nuclei. In this work, similar OES studies will be conducted for neutron-deficient nuclei by using isotopic cross sections measured in different fragmentation and spallation reactions. In addition, the OES magnitudes evaluated from comprehensive experimental data will be benchmarked with some other experimental data from different fragmentation and spallation reactions over a wide energy range. Finally, for both neutron- and proton-rich nuclei, the OES magnitudes of isotopic cross sections calculated by two empirical models, namely, FRACS [53] and SPACS [54], will be checked by comparing with the OES evaluated from extensive experimental data.

II. ODD-EVEN STAGGERING IN EXPERIMENTAL CROSS SECTIONS

The staggering effect and the impact of nuclear structure effects become very obvious along a constant isospin T_z chain, as demonstrated in Refs. [8,9,43,53]. Due to this, the magnitude of the OES in isotopic cross sections is calculated for four neighboring nuclei (centered at $Z + 3/2$) along a constant $T_z = (N - Z)/2$ chain by employing the following third-order difference equation [8,9,43,53,55]:

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

$Y(Z,N)$ is the production cross section or yield value of a particular nucleus with an atomic number Z and a neutron number $N = Z + 2T_z$. For the calculated $D_{\rm CS}(Z,N)$, the absolute value indicates the strength of the OES and a positive (negative) value means an enhanced production of even-Z (odd-Z) nuclei.

On the neutron-deficient side, accurate measurements of isotopic cross sections reach around $N - Z = -4$ nuclei near the proton drip line. Their cross sections have been accurately measured in the following fragmentation or spallation reactions: 1000 MeV/nucleon ^{124,136}Xe + Pb [2], 140 MeV/nucleon ^{40,48}Ca + Be/Ta [5], 140 MeV/nucleon ^{58,64}Ni + Be/Ta [5], 483 MeV/nucleon ^{78}Kr + Be [8], 463 MeV/nucleon ^{58}Ni + Be [9], 650 MeV/nucleon ^{58}Ni + Be [25], ^{56}Fe + p at 300, 500, 750, 1000, and 1500 MeV/nucleon [44], and 1000 MeV/nucleon ^{136}Xe + p [45]. In most of the above experiments, a relative uncertainty of less than 15% has been achieved, while it is larger than 20% for few data measured in ^{58}Ni + Be at 650 MeV/nucleon [25]. To avoid possible staggering structures resulting from large errors in experimental data, the above accurate experimental cross sections are used to calculate the OES magnitudes.

For neutron-deficient fragments with $(N - Z)$ from 0 to -4, Fig. 1 shows the OES magnitudes calculated by Eq. (1) using accurate cross sections measured in the above-mentioned fragmentation or spallation reactions with different projectile-target combinations over a wide energy range [2,5,8,9,25,44,45]. A positive OES is observed for almost all measured neutron-deficient fragments with $(N - Z)$ from 0 to -4, which is caused by a large proton separation energy for even-Z nuclei but a small one for odd-Z nuclei [8,9]. For $N = Z$ nuclei, the OES tends to decrease as Z increases and the largest OES value of about 50% is reached around $Z = 7$ and 13, where the OES in the proton separation energy shows very similar tendencies. For $N - Z = -1$ nuclei, a biggest OES value around 60% is observed at $Z = 20$ and 28, which is caused by the strong shell impact. For $N - Z = -2$ nuclei, the shell impact is also evident and the OES is highest around $Z = 20$. For $N - Z = -3$ and -4 nuclei close to the proton drip line, only few experimental data exist. As shown in Fig. 1, all experimental data from different spallation and fragmentation systems show the same evolution tendency along a constant isospin chain and they are also in good agreement within their uncertainties.

Based upon the systematic OES studies for measured cross sections of neutron-deficient nuclei in this work and neutron-rich ones in Ref. [43], comparisons of all accurate experimental data (about 4200) reveal that the OES magnitude almost does not depend on the projectile-target combinations or the projectile energy and it seems to be a universal quantity for different fragmentation and spallation reactions over a broad energy range.

III. EVALUATION OF ODD-EVEN STAGGERING

For some empirical models, e.g., FRACS [53] and SPACS [54], an accurate evaluation of the OES magnitude is required to improve their calculations for isotopic cross sections in fragmentation as well as spallation reactions. Considering the universality of the OES magnitude for different fragmentation and spallation systems, the above accurate experimental data of neutron-deficient nuclei can be applied to derive the evaluation value of the OES magnitude for various reactions by using the same method as described in Ref. [43].

For a specific nucleus with atomic number Z and neutron number N, the evaluated OES magnitude $D_{\rm CS}^{\rm eval}$ can be calculated from the weighted average of the OES magnitudes of the above experimental data from different reactions by the following formula:

$$D_{\rm CS}^{\rm eval}(Z,N) = \frac{\sum_{i=1}^{n} \frac{D_{\rm CS}^{i}(Z,N)}{(\sigma^i)^2}}{\sum_{i=1}^{n} \frac{1}{(\sigma^i)^2}}. \tag{2}$$

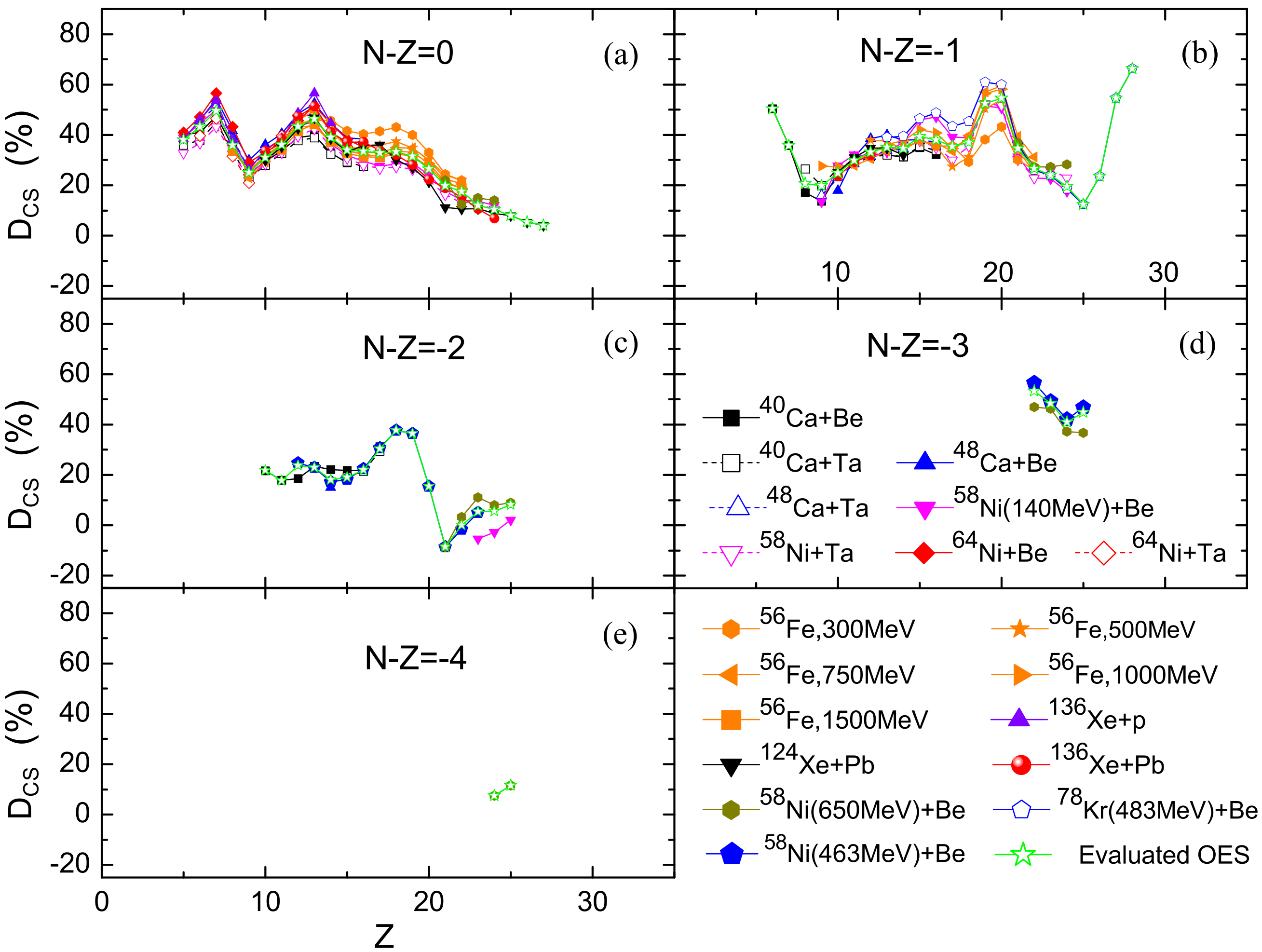

FIG. 1. The OES magnitudes calculated by Eq. (1) using experimental data of 19 different reaction systems, i.e., 1000 MeV/nucleon ^{124,136}Xe + Pb [2], 140 MeV/nucleon ^{40,48}Ca + Be/Ta [5], 140 MeV/nucleon ^{58,64}Ni + Be/Ta [5], 483 MeV/nucleon ^{78}Kr + Be [8], 463 MeV/nucleon ^{58}Ni + Be [9], 650 MeV/nucleon ^{58}Ni + Be [25], ^{56}Fe + p at 300, 500, 750, 1000, and 1500 MeV/nucleon [44], and 1000 MeV/nucleon ^{136}Xe + p [45]. The evaluated magnitudes (green open stars) are obtained from the weighted average of the above measured OES values by using Eq. (2). For clarity, experimental error bars (around 8% in most cases) are not shown. The data are shown from (a) $N - Z = 0$ to (e) $N - Z = -4$.

n is the number of experimental data sets, while D^i_{CS} and σ^i are the OES magnitude of this nucleus and its error, respectively, which are derived from one experimental data set. The evaluated OES magnitudes (green open stars) are also in good agreement with those OES magnitudes in various experimental data, as displayed in Fig. 1. According to comparisons of the evaluated OES magnitudes and experimental data from different reactions, the error of the evaluated OES magnitude is around 8%, which stems mainly from the uncertainty of experimental data and a possible small dependence of the OES on the reaction system. The above OES magnitudes evaluated from extensive experimental data can be used to improve the fragmentation and spallation models (e.g., FRACS [53] and SPACS [54], respectively) and accurately calculate the production cross sections of fragments. However, before this, one should validate the evaluated OES magnitudes with some additional experimental data and check the OES magnitudes predicted by these models.

IV. COMPARISON WITH OTHER EXPERIMENTAL DATA

The evaluated OES magnitudes reported in Ref. [43] and this work (green open stars in Fig. 1) will be benchmarked with some other experimental data sets from different fragmentation and spallation reactions over a wide energy range. These experimental data sets usually have much larger uncertainties, which may lead to spurious staggering structures, and thus are not used in the above calculations of evaluated OES magnitudes.

The OES magnitudes calculated by Eq. (1) using experimental data from two fragmentation reactions, namely, 1 GeV/nucleon ^{238}U + Ti [34] and 35 MeV/nucleon ^{84}Kr + ^{124}Sn [12], are shown in Fig. 2, by open circles and filled squares, respectively. The OES magnitudes from the fragmentation of both the heavy projectile ^{238}U at 1 GeV/nucleon and the medium-mass projectile ^{84}Kr at 35 MeV/nucleon are in remarkable agreement with the evaluated magnitudes, derived from extensive experimental data accurately measured in

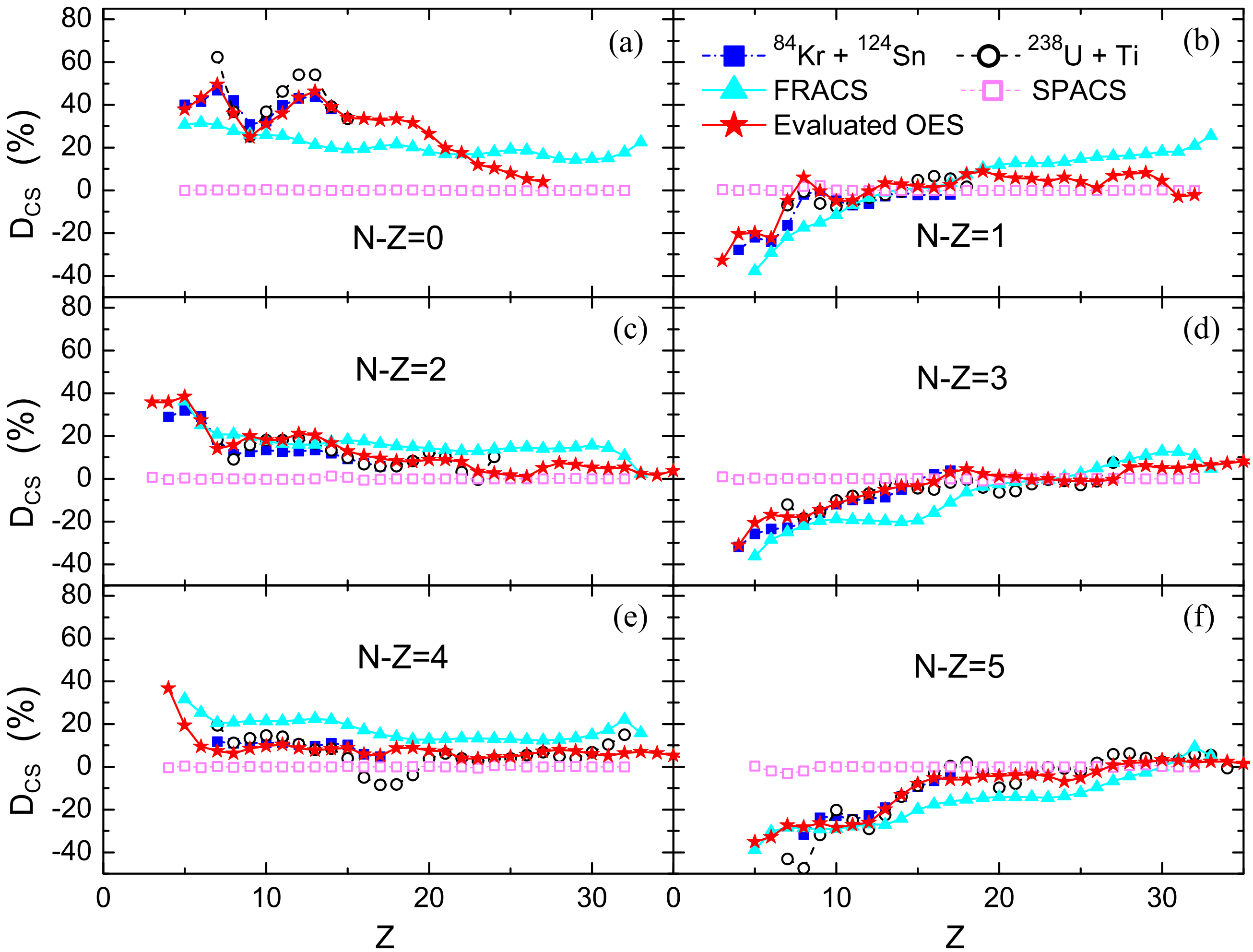

FIG. 2. The evaluated OES magnitudes (red stars), which are derived from extensive experimental data accurately measured in various spallation and fragmentation reactions, are compared with OES magnitudes calculated by Eq. (1) using two additional experimental data sets from different fragmentation reactions, namely, 1 GeV/nucleon ^{238}U + Ti [34] (circles) and 35 MeV/nucleon ^{84}Kr + ^{124}Sn [12] (blue squares). For clarity, experimental error bars (around 10% for ^{84}Kr fragmentation but much larger than 10% for ^{238}U fragmentation) are not shown. The OES magnitudes for reactions of ^{238}U predicted by two empirical models, i.e., FRACS [53] and SPACS [54], are also presented. The data are shown from (a) $N - Z = 0$ to (f) $N - Z = 5$.

various spallation and fragmentation reactions. Along a constant $N - Z$ chain, the OES magnitudes in two experimental data sets (from different reaction systems at different energies) also present almost the same evolution tendency as the evaluated magnitudes.

To further validate the evaluated OES magnitudes, Fig. 3 represents a comparison between the evaluated OES magnitudes (red stars) for some isotopes with $Z = 34$ as well as $Z = 35$ and the OES magnitudes in recent experimental cross sections of these fragments produced by the spallation of ^{90}Sr on both proton and deuteron targets at 185 MeV/nucleon [11]. The small OES magnitudes (around 0) shown in two experimental data sets with different targets also agree well with the evaluated ones.

It should be mentioned that the evaluated OES magnitudes are also in very good agreement with the OES magnitudes in many other experimental data sets, e.g., the spallation of ^{137}Cs on proton as well as deuteron targets at 185 MeV/nucleon [11] and 500 MeV/nucleon ^{208}Pb + p [1], although not shown in this work. All above comparisons strongly support that the OES magnitude is a universal quantity for different fragmentation as well as spallation reactions and the OES magnitudes evaluated from a large variety of experimental data can be applied in both fragmentation and spallation models to accurately calculate the isotopic cross sections.

V. COMPARISON WITH EMPIRICAL MODELS

To check the OES factors in two recent empirical models, i.e., FRACS [53] and SPACS [54], the OES magnitudes in cross sections predicted by these models will be compared with the evaluated OES magnitudes determined from extensive experimental data in this work and Ref. [43].

In Figs. 2 and 3, the OES magnitudes predicted by FRACS [53] and SPACS [54] are checked by comparison with those from experimental data. The OES magnitudes calculated by SPACS are around 0 for fragments produced by spallation of ^{238}U, which disagrees with those from experimental data.

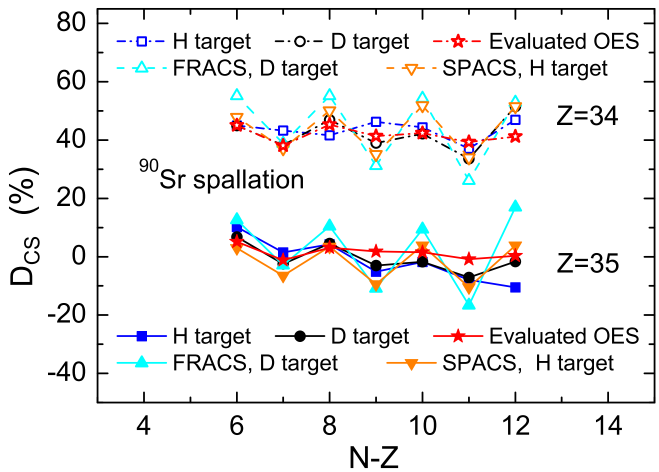

FIG. 3. The evaluated OES magnitudes (red stars) for some isotopes with $Z = 34$ as well as $Z = 35$ are compared with the OES magnitudes derived from production cross sections measured by the spallation of ^{90}Sr on proton (blue squares) and deuteron (circles) targets at 185 MeV/nucleon [11]. They are also compared with the OES magnitudes predicted by two empirical models, i.e., FRACS [53] and SPACS [54]. For clarity, a value of 40% has been added to all $Z = 34$ data. It should be emphasized that the error bars of experimental data, which are not shown, are less than 8% in most cases.

Although some discrepancies, FRACS calculations are in better agreement with experimental data, as shown in Fig. 2. Furthermore, for some isotopes with $Z = 34$ as well as $Z = 35$ in Fig. 3, SPACS and FRACS calculations for reactions on proton and deuteron targets, respectively, are in generally good agreement with measured data.

The OES magnitudes in cross sections predicted by FRACS and SPACS for two reactions, namely, $^{56}\mathrm{Fe} + p$ and $^{136}\mathrm{Xe} + p$ at 1 GeV/nucleon, are also calculated by Eq. (1) and are compared with those evaluated from many experimental data, as presented in Fig. 4. In FRACS, the OES magnitude is the same for one fragment produced in different reactions, which is supported by extensive experimental data measured in various fragmentation and spallation reactions. In SPACS, the OES magnitudes are large for $^{56}\mathrm{Fe} + p$, but they are almost 0 for $^{136}\mathrm{Xe} + p$, which is obviously inconsistent with many experimental data from different reactions. Furthermore, large discrepancies are observed between predictions by FRACS as well as SPACS and the OES magnitudes evaluated from many experimental data; see, e.g., panels (a), (e), and (g) of Fig. 4.

Although the OES has been considered in recent empirical models, i.e., FRACS [53] and SPACS [54], further improvements of these models are still needed to reproduce the OES observed in various fragmentation and spallation reactions and accurately calculate the isotopic cross sections, according to the above comparisons (for fragments with $N - Z$ from -3 to 9 in Figs. 2 and 4). For both neutron- and proton-rich nuclei, the OES magnitudes evaluated from extensive experimental data are recommended to be implemented in fragmentation

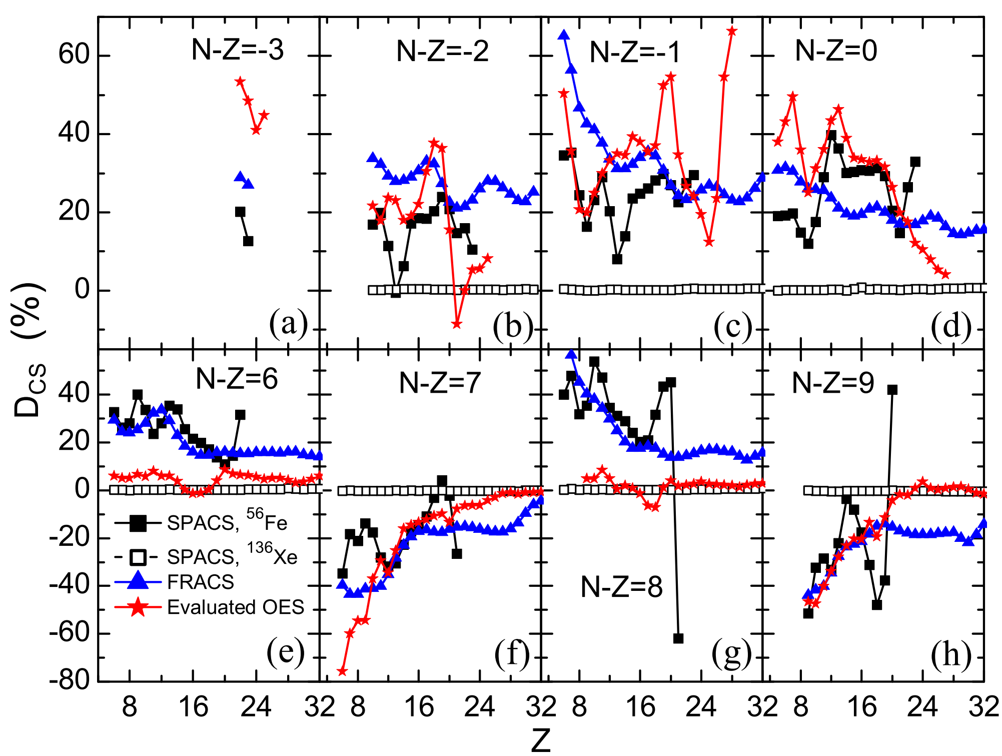

FIG. 4. Comparison between the OES magnitudes in the isotopic cross sections predicted by two empirical models, namely, FRACS [53] (blue triangles) and SPACS [54] (black squares), and the OES magnitudes (red stars) evaluated from extensive experimental data. In SPACS, the OES magnitudes are different for two reactions, namely, the spallation of ^{56}Fe (filled squares) and ^{136}Xe (open squares) on proton targets at 1000 MeV/nucleon.

and spallation models in order to improve their predictions for the isotopic cross sections. When the OES magnitudes cannot be evaluated from fragmentation or spallation experimental data, the above empirical models can use the OES magnitudes estimated from the nucleon separation energies, which can be obtained from measured data or theoretical models; see Refs. [53,54] for details.

VI. SUMMARY

In summary, the OES effect in cross sections of neutron-deficient nuclei produced by both fragmentation and spallation reactions is quantitatively investigated. For the neutron-deficient nuclei with $(N - Z)$ from 0 to -4, the OES magnitudes in their production cross sections are calculated by a third-order difference formula using many experimental data accurately measured in different fragmentation and spallation reactions. These OES magnitudes from different reactions are in good agreement within their uncertainties and they are almost independent of the projectile-target combinations and the bombarding energy. For both neutron- and proton-rich nuclei, the OES magnitudes evaluated from many experimental data are also benchmarked with some additional experimental data from different reactions over a wide energy range. At last, the OES factors in two recent fragmentation and spallation models, namely, FRACS [53] and SPACS [54], respectively, are checked by comparing with the OES magnitudes evaluated from extensive experimental data. According to this comparison, further improvements of the OES factors in these models are required to accurately calculate fragmentation and spallation cross sections. The OES magnitudes reported in this work and Ref. [43], evaluated from extensive experimental data, are strongly suggested for both fragmentation and spallation models.

ACKNOWLEDGMENTS

This research was supported by the SYSU 100 Top Talents Program, and the ELI-NP Phase II, a project co-financed by the Romanian Government and the European Union through the European Regional Development Fund - the Competitiveness Operational Programme (1/07.07.2016, COP, ID 1334).

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