N and *Z* odd-even staggering in Kr + Sn collisions at Fermi energies

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The odd-even staggering of the yield of final reaction products has been studied as a function of proton (Z) and neutron (N) numbers for the collisions ^{84}Kr + ^{112}Sn and ^{84}Kr + ^{124}Sn at 35 MeV/nucleon in a wide range of elements (up to $Z \approx 20$). The experimental data show that staggering effects rapidly decrease with increasing size of the fragments. Moreover the staggering in N is definitely larger than the one in Z. Similar general features are qualitatively reproduced by the GEMINI code. Concerning the comparison of the two systems, the staggering in N is in general rather similar, being slightly larger only for the lightest fragments produced in the n-rich system. In contrast the staggering in Z, although smaller than that in N, is sizably larger for the n-poor system with respect to the n-rich one.

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I. INTRODUCTION

The odd-even staggering in the yields of reaction products is a feature that has been observed for many years in the charge distributions of a large variety of nuclear reactions. This phenomenon has been extensively studied in relation to fission fragments of actinide nuclei (see, e.g., Refs. [1–4] and references therein) and has been attributed to pairing effects in the nascent fragments.

Odd-even staggering has been observed also in light fragments produced by fragmentation or spallation at relativistic energies (see, e.g., [5–8]) and more recently even in heavy-ion collisions at Fermi energies ($15 \lesssim E/A \lesssim 50$ MeV/nucleon) [9–13]. The study of odd-even effects has gained renewed interest from this last finding. In fact, in order to study the symmetry energy [14–16], one needs to reliably estimate the primary isotopic distributions of fragments and this is possible only if the effects of secondary decays are small or sufficiently well understood.

Usually the staggering consists of even-Z fragments presenting systematically higher yields with respect to the neighboring odd-Z ones. When isotopic identification is achieved (as in spectrometer-based experiments), additional features emerge: for example, fragments with $N = Z$ show a particularly strong staggering, while fragments with odd difference $N - Z$ present a reverse staggering ("antistaggering"), favoring the production of fragments with odd Z [7,17,18]. Moreover, if systems with different N/Z are compared, the n-poor system shows an enhanced staggering in the charge distribution with respect to the n-rich one [9,12,17], while the opposite is observed for the N distribution [12].

In low-energy heavy-ion collisions, the odd-even staggering may be a signature of nuclear structure effects in the reaction mechanism, if part of the reaction proceeds through very low excitation energies [19]. In collisions at intermediate (or Fermi) energies the preferred interpretation is that structure effects are restored in the final products of hot decaying nuclei and that the odd-even staggering depends—in a complex and presently not very well understood way—on the structure of the nuclei produced near the end of the evaporation chain [7,17,20]. At present, no theoretical model exists that is able of reproducing all the details of the observed staggering, although some general characteristics are reproduced. For example, in Ref. [17] a staggering effect is observed in events simulated with the GEMINI code [21], where staggering originates from the mass and level density parametrization that includes a pairing contribution [22], fading out with increasing excitation

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energy and spin. In the improved quantum molecular dynamics (ImQMD) simulation of Ref. [23], the produced fragments do not present even-odd effects unless their decay is taken into account by using GEMINI as an afterburner. A comparison with the results of ISMM [24] is presented in Ref. [18], where staggering is attributed to a pairing-dependent term, rapidly oscillating as a function of Z, that affects an otherwise smooth distribution.

In this work we present an analysis of the data taken by the FAZIA Collaboration [25] in the collisions ^{84}Kr + ^{112}Sn (henceforth "n-poor" system) and ^{84}Kr + ^{124}Sn ("n-rich" system) at a bombarding energy of 35 MeV/nucleon. The odd-even staggering effects are investigated as a function of atomic number (Z staggering) and neutron number (N staggering) for the two colliding systems. Some comparisons with the results of GEMINI and with other experimental data available in the literature are presented too.

II. SETUP AND EXPERIMENTAL RESULTS

The experiment was performed at the Superconducting Cyclotron of LNS (Laboratori Nazionali del Sud) of INFN in Catania. A pulsed beam of ^{84}Kr at 35 MeV/nucleon was used to bombard two targets of ^{112}Sn (areal density 415 μg/cm^2) and ^{124}Sn (areal density 600 μg/cm^2). Reaction products were detected in a Si-Si-CsI(Tl) telescope of the FAZIA Collaboration (thicknesses: 300 μm, 500 μm, and 10 cm, respectively), covering the angular range between 4.8° and 6°, close to the grazing angles of the two reactions (4.1° for the n-poor system and 4.0° for the n-rich system). The same set of data was analyzed also in a recent paper [26], where the good performances of the FAZIA telescope in terms of charge and mass identification capability were used to investigate the isospin transport by means of fragments isotopically resolved up to $Z = 20$. More details on the experimental setup can be found in Refs. [26,27] while the performances of the FAZIA telescopes are illustrated in Refs. [27–31].

The present analysis concerns ions identified with the ΔE-E technique, as was done in Ref. [26]. The data were acquired in singles, so a characterization of the centrality of the collisions is not possible. However, as explained on the basis of Fig. 2 in Ref. [26], from the accessible phase-space region one can expect that most detected products are either quasiprojectile residues ($Z \sim 20$–36) or fission fragments of the quasiprojectile, with a possible component of emissions from the neck region (light fragments with velocities close to that of the center-of-mass). Since all products are forward emitted in the center-of-mass reference frame, it is reasonable to suppose that quasitarget contributions are negligible.

The experimental fragment distributions as a function of Z (N) are presented in Fig. 1 (Fig. 2) for the two investigated reactions (a) ^{84}Kr + ^{112}Sn and (b) ^{84}Kr + ^{124}Sn at 35 MeV/nucleon. As already noted in Ref. [26], the charge and mass distributions of the detected products present significant differences between the n-poor and n-rich systems, despite the fact that the projectile is the same and the accessible phase space is associated predominantly with quasiprojectile ejectiles. This fact was taken as proof of isospin diffusion. We now want to investigate how far some differences can be

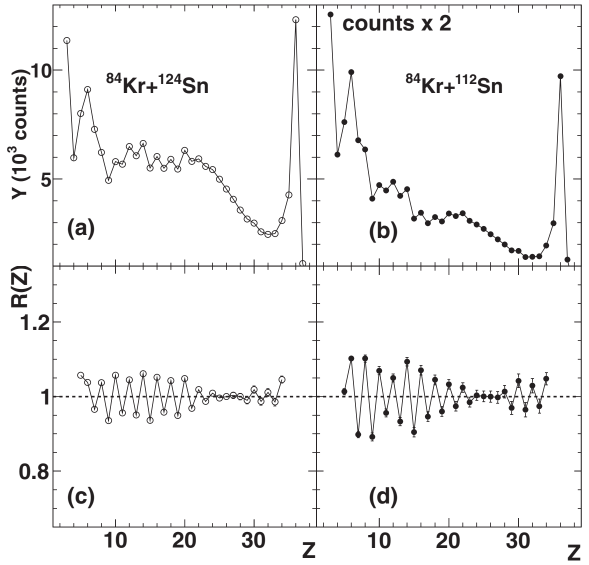

FIG. 1. Experimental Z distributions for the systems (a) ^{84}Kr + ^{124}Sn and (b) ^{84}Kr + ^{112}Sn, both at 35 MeV/nucleon. Staggering as a function of Z, highlighted by the ratio $R(Z)$ for the same systems (c) ^{84}Kr + ^{124}Sn and (d) ^{84}Kr + ^{112}Sn. Bars indicate statistical errors.

found also in the staggering of the final yields of fragments. It is worth noting that, with staggering being a differential effect between neighboring nuclei, the detection efficiencies cancel out almost exactly. Moreover, since the kinematics of the two colliding systems are very similar, also geometric effects are practically the same in the two sets of data.

To put the odd-even staggering in quantitative evidence, one has to remove from the experimental yield Y the dependence of the smoothed yield $\mathcal{Y}$ on proton or neutron numbers of the fragments. This can be obtained in various ways [1,6,17].

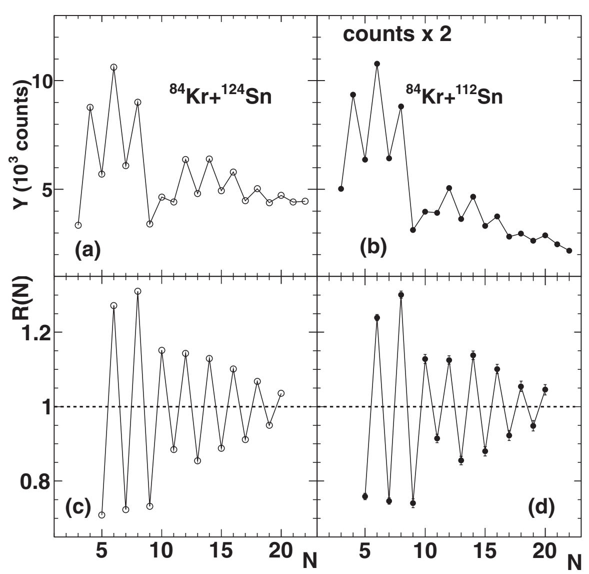

FIG. 2. Experimental N distributions for the systems (a) ^{84}Kr + ^{124}Sn and (b) ^{84}Kr + ^{112}Sn, both at 35 MeV/nucleon. Staggering as a function of N, highlighted by the ratio $R(N)$ for the same systems (c) ^{84}Kr + ^{124}Sn and (d) ^{84}Kr + ^{112}Sn. Bars indicate statistical errors.

The treatment of Tracy *et al.* [1], based on a finite difference method of third order, gives a quantitative measure of the effect and has been used by most authors. In this paper we have used a similar procedure, based on the finite differences of fourth order, that uses five data points and will be described in a forthcoming paper [32]; one advantage is that it avoids using semi-integer values of Z. We have checked that the presented results are not very sensitive to the particular method used to estimate the smooth behavior of the yield. For each point of the yield distribution, one can finally build the ratio between the experimental and the smoothed yields, $R = Y/\mathcal{Y}$, which by construction oscillates above and below the line $R = 1$ and gives a direct visual impression of the staggering.

Figures 1(c) and 1(d) display the staggering in Z by means of the ratio $R(Z)$ for the n-rich and n-poor systems, respectively. The amplitude of the odd-even effect is on average larger for the n-poor system, thus confirming the findings of previous papers [9,12,17]. Quantitatively the staggering in Z remains of the order of $\approx\pm 10\%$. For both systems, the staggering is rather pronounced at low-medium Z (up to $\sim$20), then it tends to disappear for higher Z values. Around $Z = 30$ we observe a renewed increase of the staggering, mainly in the n-poor system. A very similar behavior was observed also in Ref. [13], both in inclusive analysis and with some selection of the centrality; in that case the studied system was ^{112}Sn + ^{58}Ni at 35 MeV/nucleon.

Thanks to the good isotopic resolution of the FAZIA telescopes, it is possible here to perform an extensive analysis also for the staggering in N, for the first time in a rather wide range. Figures 2(c) and 2(d) present the staggering in N by means of the ratio $R(N)$ for the two systems. Here the N distribution does not extend beyond $N = 20$, because we have isotopic resolution up to $Z \approx 20$ (and correspondingly up to $N \approx 22$, with the method requiring two points on both sides of each N). This is the limit of our isotopic resolution in the present case.

The most apparent—and to our knowledge rather new—feature is that the staggering as a function of N is large (definitely much larger than that in Z), especially for the lighter fragments where it reaches a rather surprising value of $\approx\pm 30\%$ and slowly decreases with increasing N. Indeed it strongly differs from the typical behavior in low-energy fission, where the fission fragments usually display a staggering in N weaker than that in Z [3,33]. The second observation is that, at first sight, the isospin diffusion due to the collision with targets of different N/Z produces larger differences in the Z staggering [compare Figs. 1(c) and 1(d)] than in the N staggering [compare Figs. 2(c) and 2(d)].

As in the method originally proposed by Tracy *et al.* [1], one can use a parameter $\delta(Z) = (-1)^Z(R(Z) - 1)$ to describe in a quantitative way the behavior of staggering phenomena: a positive $\delta(Z)$ corresponds to the usual staggering that favors the production of even Z (or N); $\delta(Z) \approx 0$ means the absence of any significant staggering, while negative $\delta(Z)$ indicates a reverse effect ("antistaggering") favoring the production of fragments with odd Z (or N) values. The obtained values of the parameter δ are presented in Fig. 3, both for the staggering in Z [part (a)] and in N [part (b)]; solid symbols are for the n-poor system and open symbols are for the n-rich one.

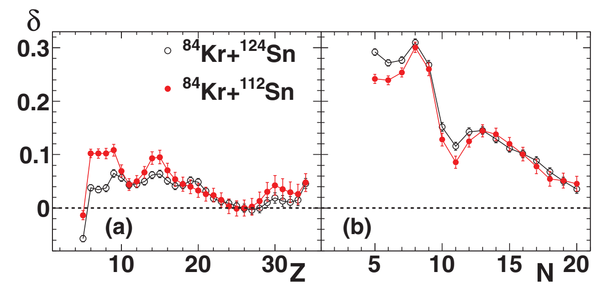

FIG. 3. (Color online) Parameter δ as a function (a) of Z and (b) of N for final fragments in the collisions ^{84}Kr + ^{112}Sn (solid symbols) and ^{84}Kr + ^{124}Sn (open symbols). Bars indicate statistical errors.

The main characteristics, already visible in Figs. 1 and 2, appear even clearer in this presentation: (i) the staggering in N is significantly higher than that in Z, by a factor of about 3 or more; (ii) the staggering in N is indeed very similar for both systems (except for the marginal region $N \leqslant 7$); (iii) the staggering in Z tends to disappear above $Z = 20$ up to $Z \sim 28$, with a sudden clear bump (despite the large statistical errors) around $Z = 30$ [13], which is more pronounced for the n-poor system; (iv) the staggering in Z shows some difference between the two systems, with the n-poor system featuring higher δ below $Z = 10$, between $Z = 12$ and $Z = 18$, and around $Z = 30$. The negative value for $\delta(Z = 5)$ in Fig. 3 is caused by the missing ^{8}Be, which distorts the needed yield of Be isotopes much more than the yield of $N = 4$ isotones.

In fragmentation reactions it was observed [34] that the even-odd staggering in Z is reduced for n-rich projectiles (like ^{40}Ar) with respect to symmetric ones (like ^{36}Ar). Recently Lombardo *et al.* [12] found that also at Fermi energies an n-rich system has a reduced staggering in Z and an enhanced one in N, while the opposite happens for an n-poor system. They drew their conclusion on the basis of a parameter S (obtained from the squared deviations with respect to a polynomial fit to the yield distributions in the interval $4 \leqslant N \leqslant 13$ or $4 \leqslant Z \leqslant 13$, see Ref. [12]) that summarizes in a single number the average importance of the staggering in each system. Applying that procedure to our case would give too rough an approximation, because our distributions span a range more than twice as large and hence a simple polynomial fit would give a poor description of the smoothed distributions. Therefore we prefer to apply our procedure also to their data and we present in Table I averaged values of the parameter δ, obtained in different ranges of Z and N.

Our results show that the staggering in N is definitely larger than that in Z, by a factor between 2 and 5. Concerning the comparison of the two systems, ^{84}Kr + ^{112}Sn and ^{84}Kr + ^{112}Sn, the staggering in N is the same within errors when evaluated over the full distributions, thus supporting the visual impression already conveyed by Fig. 1. However, if only nuclei in the range $4 \leqslant N \leqslant 13$ are used for averaging (the range of the data used in Ref. [12]), then it appears that also in our case the n-rich system has a slightly enhanced staggering in N (0.242 ± 0.003 vs 0.224 ± 0.004), which is mainly due to the lightest nuclei with $N \leqslant 7$. In contrast, the weaker staggering in Z displays a difference of about a factor of 2 between

TABLE I. Average value of the staggering parameter $\langle\delta\rangle$ as a function of N and Z for the systems Kr + Sn of this paper and Ca + Ca [12]. For Ca + Ca, relative yields and errors are estimated from Fig. 3 of Ref. [12]. For Kr + Sn the averages are evaluated in different ranges of Z and N, the first one being the same used for the data of Ref. [12].

System	Energy	(N/Z)			$10^3\langle\delta_Z\rangle$			$10^3\langle\delta_N\rangle$		Ratio $\langle\delta_N\rangle/\langle\delta_Z\rangle$	
	[MeV/u]	Proj.	Targ.	Tot.	$Z=6$–11	5–18	5–34	$N=6$–11	5–18	$Z, N=6$–11	5–18
^{84}Kr + ^{112}Sn	35	1.33	1.24	1.28	91 ± 4	68 ± 3	53 ± 2	224 ± 4	173 ± 3	2.5 ± 0.1	2.5 ± 0.2
^{84}Kr + ^{124}Sn	35	1.33	1.48	1.42	44 ± 3	40 ± 2	30 ± 1	242 ± 3	171 ± 2	5.4 ± 0.3	4.3 ± 0.3
^{40}Ca + ^{40}Ca	25	1.0	1.0	1.0	167	–	–	71 ± 5	–	0.43	–
^{40}Ca + ^{48}Ca	25	1.0	1.4	1.2	87	–	–	83 ± 10	–	0.95	–
^{48}Ca + ^{48}Ca	25	1.4	1.4	1.4	27	–	–	200	–	7.4	–

the two systems (in fair agreement with Ref. [12]), which in our case persists almost independently of the considered range of Z. The small change in the N staggering with respect to that observed in Ref. [12] is certainly due to the smaller N/Z leverage obtainable by isospin diffusion, with respect to comparing isospin-equilibrated systems (from ^{40}Ca + ^{40}Ca to ^{48}Ca + ^{48}Ca in Ref. [12]). However it is surprising that our small N/Z leverage is so much more effective in producing large differences in the Z staggering than in the N staggering.

The last two columns of Table I give the ratios $\langle\delta_N\rangle/\langle\delta_Z\rangle$ between the staggering parameters in N and Z, evaluated in a common range. For light fragments (Z and N up to 11), the clear prevalence of N staggering over Z staggering is stronger in the n-rich system than in the n-poor one, a fact that can be inferred also from the data of Ref. [12]. This effect is slightly reduced in the larger range of Z and N up to 18. It is worth noting the systematic dependence of the staggering phenomena on isospin that is displayed by both experiments, despite the differences in total mass and bombarding energy. With increasing N/Z of the systems, the decrease of the staggering in Z is accompanied by an increase of the staggering in N. As a consequence, the ratio $\langle\delta_N\rangle/\langle\delta_Z\rangle$ evolves from about 0.5 for symmetric matter ($N/Z = 1.0$) to about 7 for the very asymmetric case ($N/Z = 1.4$).

If one takes a look at the one-proton (one-neutron) separation energies as a function of Z (N) for various N (Z), one finds a clear staggering, mainly due to pairing effects, but there is no apparent difference between protons and neutrons. Tentatively, one may relate the different magnitude of the staggering in Z and N to the common assumption that pairing correlations, similarly to shell effects, should be washed out with increasing excitation energy. Proton emission is expected to be more probable in the early steps of the evaporation (where the excitation energy is higher) rather than in the last ones, unless the system is very n-poor as in the case of ^{40}Ca + ^{40}Ca. Therefore proton emission might be less sensitive to pairing effects than neutron emission, which is expected to prevail in the last steps, also because it is insensitive to the repulsive effect of the Coulomb barrier.

To gain some more insight, we performed calculations with the code GEMINI for the statistical decay (evaporation and sequential fission followed by statistical evaporation) of nuclei with initial excitation energy and spin corresponding to a semiperipheral collision. The calculated results are found to be not very sensitive to moderate variations of the input parameters. The experimental gross features of Fig. 3 are qualitatively reproduced. For example, in Figs. 4(a) and 4(b) the parameter δ is presented as a function of Z and N for two decaying nuclei with 2.7 MeV/nucleon of excitation energy and spin $J = 50$. One nucleus (squares) is the ^{84}Kr projectile, the other (dots) is a slightly lighter nucleus of ^{74}Ge, chosen to simulate some pre-evaporative emission, e.g., in the case of midvelocity or pre-equilibrium phenomena. The magnitude of the N staggering is comparable to that of the experiment and rapidly decreases with increasing N; the magnitude of the Z staggering clearly remains below that of the N staggering. A more detailed reproduction of the experimental data is not attempted, because the initial distribution of decaying primary reaction products is unknown and cannot be simulated by the decay of a single nucleus with a single value of the excitation energy and spin.

In the literature, the staggering in Z has been often looked at for chains of constant neutron excess $N - Z$ [7,17,18]. Figure 5 shows this presentation of the data for the system ^{84}Kr + ^{124}Sn. Similar results are obtained for the other system, ^{84}Kr + ^{112}Sn. In the upper left panel there are the chains with even $N - Z$ and in the upper right one there are the chains with odd $N - Z$. One sees that the $N = Z$ chain displays by far the largest positive staggering, namely, a strong enhancement of even Z with respect to the neighboring odd values resulting in positive values of δ. The effect for the other chains with even $N - Z$ is definitely smaller. In contrast, chains with odd $N - Z$ seem to display a negative staggering (or antistaggering), namely, a depression of the yields of even Z (negative values of δ), which appears to be stronger for nuclei with larger values of $N - Z$.

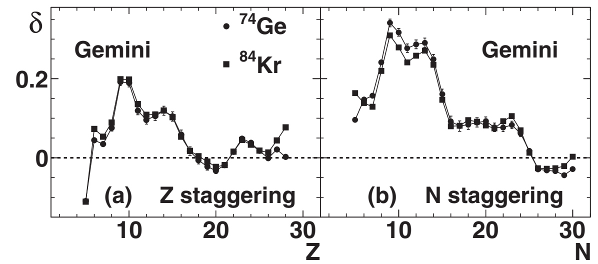

FIG. 4. Parameter δ for the staggering in Z (a) and N (b) from GEMINI simulations of the decay ^{84}Kr (solid squares) or ^{74}Ge (solid circles) at 2.7 MeV/nucleon of excitation energy.

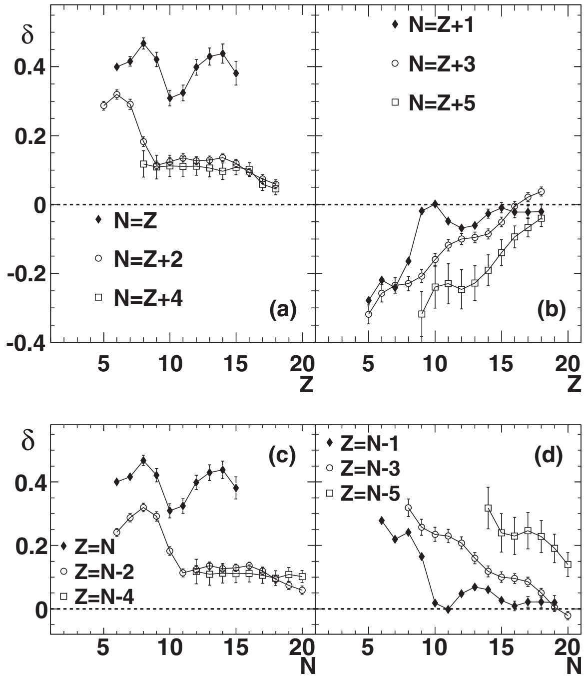

FIG. 5. Parameter δ from the experimental data of the reaction ^{84}Kr + ^{124}Sn, plotted as a function of Z for even (a) and odd (b) chains of neutron excess $N - Z$ and as a function of N, again for even (c) and odd (d) chains of $N - Z$. Note the larger vertical scale with respect to Fig. 3.

A similar qualitative behavior (although with much larger uncertainties) is observed in Fig. 4 of Ref. [7] for the fragmentation of 1 GeV/nucleon ^{238}U in a titanium target and an even quantitative agreement is found with the data of Fig. 11 of Ref. [8], concerning the spallation of 1 GeV/nucleon ^{136}Xe in a liquid hydrogen target.

The general behavior observed in Fig. 5 can be understood simply from the fact that there is staggering in *both* N and Z (i.e., even N and Z values are enhanced and odd ones are depressed) and the effect is larger in N than in Z. The staggering is thus intensified for the even $N - Z$ chains of Fig. 5(a), which are formed only by even-even nuclei (benefiting from both enhancements) and odd-odd nuclei (depressed by both effects). In case of odd $N - Z$ chains, the nuclei are always odd-even or even-odd and therefore the staggering in N and Z works in opposite directions. The net result is that even Z are depressed due to the prevalent effect of odd N contributions and, conversely, odd Z are enhanced due to the prevalent effect of even N: the net result is the moderate *seeming* antistaggering visible in Fig. 5(b).

The same data can be plotted as a function of the neutron content N of the fragments, as shown in the lower panels of Fig. 5. The points are exactly the same as in the upper panels; there are just horizontal shifts for the various chains and an additional change of sign for all chains corresponding to odd-A nuclei in Fig. 5(d) with respect to Fig. 5(b). Therefore the *seeming* antistaggering in Z, commonly observed for odd-mass nuclei, is an artifact of the selection: in reality the production of final fragments is intensified for even Z and even N nuclei, with a more pronounced effect for the N "pairing". This is at variance with what has usually been observed in low-energy fission.

III. SUMMARY AND CONCLUSIONS

In summary, we have investigated the odd-even staggering effects in the yields of fragments produced in two reactions with the same beam of ^{84}Kr at 35 MeV/nucleon and two different targets, one n-rich (^{124}Sn) and one n-poor (^{112}Sn). The data were collected by the FAZIA Collaboration by means of a telescope located close to the projectile grazing angle. The high resolution of the telescope allowed us to obtain good isotopic identification for all ions in a wide range up to $Z \approx 20$.

The staggering was studied for complex fragments emitted in the phase space of the quasiprojectile (residues, fission products, midvelocity products). For the present analysis, the usual parameter δ [1], which allows one to perform quantitative comparisons among different sets of data, has been slightly modified [32]. The staggering of medium-light fragments has been extensively analyzed as a function of both the atomic number Z and the neutron number N, for the first time over a rather wide range. It is found that, for a given reaction, the staggering in N is definitely larger than that in Z. In agreement with other authors [9,12,17], we observe in the n-poor system a larger staggering in Z with respect to the n-rich one, while the staggering in N is in general rather similar, being slightly larger only for the lightest fragments produced in the n-rich system. However the difference between the two systems is smaller for the staggering in N and varies with the considered range in N. Simulations with the GEMINI code [21] qualitatively reproduce the larger effect for N staggering.

The staggering in Z for selected values of the neutron excess $N - Z$ presents features similar to those already reported in the literature [7,17,18]. Qualitatively they arise from the interplay between staggering in Z and N. The production of final fragments is intensified for even values of both Z and N, with the latter dominating over the former. The reason why the staggering in N is larger than that in Z and their dependence on isospin remain for the moment not fully understood and deserve further investigations. They will strongly benefit from the future availability of unstable radioactive beams and from the development of high-resolution detectors, covering large solid angles and coupled with setups capable of a good characterization of the events.

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