Persistence of odd-even staggering in charged fragment yields from the $^{112}$Sn+$^{58}$Ni collision at 35 MeV/nucleon

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Odd-even staggering effects on charge distributions are investigated for fragments produced in semiperipheral and central collisions of $^{112}$Sn+$^{58}$Ni at 35 MeV/nucleon. For fragments with Z ≤ 16 one observes a clear overproduction of even charges, which decreases for heavier fragments. Stag-

gering persists up to Z ∼ 30. It appears to be substantially independent of the centrality of the collisions, suggesting that it is mainly related to the last few steps in the decay of hot nuclei.

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An enhanced production of even-Z fragments with respect to odd-Z ones has been observed since long time in a variety of nuclear reactions (1, 6) and references therein). The enhancement in the yield of even ele-
ments over the neighboring odd ones is usually of the order of few tens per cent for the lightest elements and it rapidly decreases with increasing Z. Recent experiments (2, 6, 7), performed with detectors providing good iso-
topic resolution, revealed a rather complex behavior. It was found that even-mass fragments display indeed an odd-even staggering with an enhanced yield of even-Z nuclei. This effect is particularly prominent for N=Z fragments, where it becomes of the order of 50%. On the contrary, odd-mass fragments display a weaker re-
verse staggering, which favors odd-Z nuclei (3, 6). The overall odd-even effect usually reported in literature results from the superposition of these different behaviors. By comparing colliding systems with different N/Z, it was concluded that the staggering on Z distributions (integrated over all isotopes) is enhanced for neutron-poor systems (1, 6). In turn, the staggering on N-distributions (integrated over all isotopes) is enhanced for neutron-rich systems (7). There are also indications for a weakening of the odd-even Z staggering with increasing centrality of the collision (5).

The odd-even staggering is believed to be a signature of nuclear structure effects (3, 6). They may manifest them-

selves just in the reaction mechanism, if part of the reaction proceeds through low excitation energies (8). How-

ever, in collisions at intermediate 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 (3, 6).

While the odd-even staggering is an interesting topic in itself, renewed interest has been stirred by recent observations of such phenomena in fragments produced in heavy ion collisions at intermediate energies (15 ≤ E/A ≤ 50 MeV/nucleon). Indeed, in order to study the symmetry energy (3, 11) one needs to reliably estimate the primary isotopic distributions and this is possible only if the ef-

fects of secondary decays are small or sufficiently well understood.

This paper presents an experimental investigation of the odd-even staggering in the fragment charge distribution of the asymmetric collision $^{112}$Sn + $^{58}$Ni at 35 MeV/nucleon. The data extend the available systemat-
ics for the first time to a higher charge range, from Z=6 to Z∼45. A self-supporting $^{58}$Ni target (200 µg/cm² thick) was bombarded by a pulsed $^{112}$Sn beam (of ≈ 1 ns time resolution), delivered by the Superconducting Cyclotron of the Laboratori Nazionali del Sud of INFN in Catania. Reaction products were detected with the CHIMERA multidetector (12, 13) in the complete configuration consisting of 1192 telescopes. They are mounted at polar angles from 1° to 176°, in an axially symmetric configuration around the beam axis with a nominal geometric coverage.
of \( \approx 94\% \) of 4\( \pi \). Each telescope, made of a 300 \( \mu \)m-thick silicon detector followed by a CsI(Tl) scintillator, measures both the deposited energy and the time-of-flight of the reaction products (with flight paths from 3 to 1 m below 30° and of 40 cm for larger angles) [12, 13].

If the products have enough energy to reach the CsI scintillator, they are identified in charge either with the \( \Delta E-E \) technique, or (if they are fast light particles) with the usual fast-slow analysis of the CsI signal shape. In this way all charges can be individually identified from \( Z=1 \) up to the charge of the projectile (\( Z=50 \)), with a typical FWHM resolution of about 0.4 (0.5) charge units at \( Z=20 \) (50), while isotopic identification is obtained up to Carbon. The thresholds for \( Z \) identification vary from about 6 MeV/nucleon for Light Charged Particles (LCP, \( Z \leq 2 \)) to about 23 (27) MeV/nucleon for Ni (Sn) ions. Below these thresholds, the reaction products are stopped in the silicon detectors and for an *average* estimate of the charge one must rely on the mass, obtained from the energy vs. time-of-flight (ToF) correlation. However, the resolution is limited by the overall ToF resolution (beam + detector) and by the length of the available flight-paths. Moreover, heavy fragments with very low energy need important corrections to take into account energy losses in dead layers and Pulse Height Defect phenomena. Finally, the Evaporation Attractor Line (EAL) formula [14] is used for transforming the mass into an approximate estimate of the *average* charge of stopped particles (with a FWHM resolution which for Ni-like quasi-elastic recoils is about 10–12 charge units, with non-Gaussian tails). We anticipate here that particles stopped in the silicon detectors are used only in Fig. 2 and not for studying staggering phenomena. On the contrary, all charge distributions and the derived information about odd-even staggering are obtained using only reaction products which have been “well-identified-in-charge” by means of the Si-CsI correlations. The analysis presented in this paper focuses on events where three or more charged products have been detected over the whole solid angle. This condition removes elastic events and strongly suppresses quasi-elastic ones. At least two of these products are required to be fragments with charge \( Z \geq 3 \).

The experimental charge distribution of fragments is shown in Fig. 1(a). Aside from a steep rise for light products with \( Z \leq 10 \), the distribution almost flatly extends up to the projectile charge. This rather unstructured shape is due the superposition of all processes which may occur in the collision. Since odd-even effects are a rather pervasive feature, observed in many different reaction mechanisms, some information can be gained already from this inclusive analysis.

A close look at the charge distribution (see inset), shows that some staggering effect is indeed present, but the large variation of yield, especially in the low-\( Z \) region, hinders a clear appreciation of its magnitude. The smoothing procedure suggested in [8] was applied, which is able to highlight the staggering effect. For each measured value of the yield \( Y(Z) \), a smoothed value \( \bar{Y}(Z) \) is estimated with a parabolic fit to the measured yields over five consecutive points (namely, the yields of that \( Z \), and of the two preceding and the two following \( Z \)’s). The continuous line in Fig. 1(a) joins the so obtained values of \( \bar{Y}(Z) \). The ratio \( R(Z) \) between \( Y(Z) \) and the smoothed value \( \bar{Y}(Z) \) is shown in Fig. 1(b). \( R(Z) \) oscillates around 1 (dashed line) and a clear odd-even staggering is observed, with the even-\( Z \) ions being more abundantly populated than the odd ones. This bears out the gross features already observed in previous experiments [1–3, 6, 7].

The staggering is large (\( \approx 10–15\% \)) for medium-charge ions with \( Z \leq 16 \) and it decreases with increasing \( Z \). Indeed the rapid disappearance of staggering effects giving rise to a smooth behavior with increasing mass is a common observation, which has been tentatively explained with a decrease of the pairing gap and an increasing competitiveness of gamma emission with respect to particle decay [2]. It is worth noting that previous investigations of staggering effects usually stopped around \( Z=16–20 \) and none has covered up to now this large range from \( Z=6 \) to \( Z \sim 45 \). Around \( Z=30 \) we observe an enhancement, with a renewed increase of the yields of the even \( Z=30, 32 \) fragments with respect to the neighboring odd ones. An excess in the production of even elements around \( Z=30 \), similar to that of the present paper, has been observed also in the charge distributions of quasi-projectiles measured with the FIASCO apparatus [15] for similar systems at 30 and 38 MeV/nucleon. Work on this point is in progress, but at present no interpretation of this new “anomaly” around \( Z=30 \) is at hand. Trivial effects due to particular features of proton and neutron separation energies seem unlikely, since the separation energies do not show any anomalous behavior around this value of \( Z \).

The inclusive results of Fig. 1 are dominated by the high yields of peripheral collisions. For a more detailed
analysis, it is necessary to sort the events in bins of different centrality and this requires the preliminary selection of nearly “complete” events. This was obtained constraining the total reconstructed charge $Z_{tot}$ and the total longitudinal moment $p_{tot}$ to the beam momentum. For estimating these two variables—and only for this purpose—also reaction products stopped in the silicon detectors were included. The mass of non-stopped particles was deduced from the measured charge with the EAL formula.

The correlation between total reconstructed charge and total longitudinal momentum is shown in Fig. 2. The lower branch of the “fork” at high $p_{par}$ corresponds to events where the Ni-like recoil escaped detection, while the two branches at low $p_{par}$ correspond to events lacking detection of the Sn-like in one case, and of both the Sn- and Ni-like fragments in the other case. The tail of events with $Z_{tot}$ is due to fragments (mainly slow Ni-like recoils or target-like fragments) stopped in the silicon detector, for which no direct charge identification is possible, but only an average estimation from their mass. The adopted acceptance window, indicated by the rectangle in figure, requires a total reconstructed charge greater than 60% of the system charge ($Z_{tot}$) and a total longitudinal momentum greater than 60% of the beam momentum. Events with low total charge and low total momentum were rejected, as they correspond to more incomplete events. In this experiment (one of the firsts with the complete CHIMERA setup) not all telescopes delivered full information or performed equally well. Therefore a necessary compromise between exploiting a large geometric coverage and having a very good Z resolution resulted in using the best 60% of the detectors (evenly sparse over the solid angle) for the analysis of odd-even effects. The results are insensitive to this choice, since staggering effects arise from the comparison of the different production rates of nuclei with similar Z values, hitting the same detectors.

The charge distribution and staggering ratio for the selected “complete” events are indistinguishable from those of Fig. 1; at least from the reduction of the statistics by a factor of about 2. However, it is now possible to find a sorting parameter for investigating the evolution of the staggering with the centrality of the collision. In heavy ion collisions at intermediate energies the largest part of the reaction cross section corresponds to binary events, characterized by the presence in the exit channel of two heavy remnants, the quasi-projectile and the quasi-target. Together with these heavy remnants one observes LCPs and Intermediate Mass Fragments (IMF, with $3 \leq Z \leq 16$) produced by their evaporative decay and possibly by midvelocity emissions (see, e.g., [16–18]). The transverse energy of LCPs was used to estimate the centrality of the collisions [16, 19]. The transverse energy is defined as $E_{\text{transv}} = \sum_i p_{i\perp}^2 / (2m_i)$, where $p_{i\perp}$ is the transverse momentum (with respect to the beam axis) and $m_i$ the mass of the LCP. The lower part of Fig. 3 shows the transverse energy $E_{\text{transv}}$ as a function of the charge of the heaviest fragment $Z_{max}$. In semiperipheral collisions with reverse kinematics the fast, heavy, forward-going fragment is the quasi-projectile remnant and its charge is expected to decrease with increasing violence of the collision [20, 22]. The good correlation between the two variables observed in Fig. 3 indicates that, although the geometric coverage of the setup was
not complete, the transverse energy of the detected LCPs can be used as an impact parameter selector.

The upper part of Fig. 3 shows the projection (black histogram) of the same data on the Z\textsubscript{max} axis and, for comparison, also the Z distribution (color histogram) of all detected particles, from protons up to projectile-like fragments. Although the data are integrated over particle energies and summed over all used detectors, one can see a good separation of the individual elements up to the highest detected charges.

The experimental charge distributions of fragments are shown by the full points in Fig. 4(a), 4(c), 4(e) for three bins of E\textsubscript{transv}: 40–110 MeV (a), 110–180 MeV (c) and 180–250 MeV (e). Full points show the yield Y(Z) of all detected reaction products, open points that of the largest fragment Y(Z\textsubscript{max}). The continuous line joins the values Y(Z) obtained from a smoothing procedure (see text). The insets are expansions of the peaks at large Z. Statistical errors are smaller than the point size. (b), (d), (f) Corresponding ratios R between the experimental yield Y(Z) and the smoothed value Y\textsubscript{smooth}(Z) as a function of Z. Bars represent statistical errors.

The possible dependence of the odd-even staggering on the centrality of the reaction is summarized in Fig. 5. Here each point, drawn at the semi-integer value Z+\frac{1}{2} of an even-odd pair, represents the difference between the staggering ratio R(Z) for that even Z and the ratio R(Z+1) for the following odd Z+1 value. The different symbols refer to the different selections of E\textsubscript{transv} in Fig. 4 and to the central collisions. From Fig. 5
three points are worth noting. First, all distributions are very well superimposed on each other, with practically no dependence on impact parameter (at least within the sensitivity of our measurement). This seems at variance with the weak dependence on centrality found in a lighter system [6]. Second, the charge distributions of IMF (3 \leq Z \leq 16) display a strong even-odd effect, a feature which is present in all previous experiments which have investigated staggering phenomena. Also the large opposite behavior of the yields of Z=8 with respect to Z=9 (and of Z=14 with respect to Z=15) is visible in previous data [3]. Finally, the staggering effect decreases rapidly with increasing charge of the heavier fragments, except for an unexpected moderate enhancement around Z=30, which was not observed previously because of the limited range of investigated charges.

Past attempts to explain staggering effects on the base of nuclear structure effects could reproduce the experimental data only in a qualitative, but not in a quantitative way. This led to suppose that not only the available phase space at the end of the evaporation process is important, but also the number of available levels in the mother nucleus may play a role [3]. A more recent investigation assumes that it may be necessary to have a good knowledge not only of the last decay step, but of the last few ones [24], particularly for what concerns “pairing and isospin effects in the level density” at rather high excitation energies.

The selections adopted in the present paper correspond to events with different impact parameters (from peripheral to central), therefore the observation that the staggering amplitude of IMFs is independent of the reaction class demonstrates that this phenomenon keeps almost no memory of the preceding reaction dynamics. In fact, IMFs may be produced by different mechanisms, ranging from the possible multifragmentation of a “central” source to the decay of a hot quasi-projectile, via evaporation or sequential fission. This in turn supports the idea that the odd-even staggering of IMFs arises in the last few steps of their decay and may be linked to details of the structure of the involved nuclei [3, 24].

In summary, we have presented experimental data from the reaction $^{112}$Sn+$^{58}$Ni at 35 MeV/nucleon, collected with the CHIMERA multidetector during one of its first campaigns in complete configuration. The presented results focus on the charge distributions of fragments which are well identified in charge Z. We have shown, also thanks to a smoothing technique, that it is possible to evidence a clear odd-even staggering effect in the charge distribution for light-to-medium fragments, up to values around Z≈30: even-Z fragments are produced more abundantly than odd-Z ones. The amplitude of the staggering effect decreases with increasing Z. There is an “anomaly” in the region around Z=30–32, where the difference in the yields between even and odd Z nuclei increases again. This fact is as yet not understood and deserves further investigations.

The experimental data have been sorted in samples of increasing centrality, from peripheral to central collisions. From our analysis the odd-even effects persist independently of the centrality of the reaction. This suggests that staggering is little sensitive to the preceding dynamics and has to be ascribed mainly to the last steps in the decay chain of hot fragments. The current tentative interpretation is that they may be related to details of the internal structure of the near-final fragments [3, 24]. From an experimental point of view, the investigation of these phenomena will benefit from the availability of new radioactive beams and from the next generation of detectors [25], capable of extending mass and charge identification (with unit resolution) to medium-high Z nuclei, over large solid angles. This will allow to access more exotic systems and to investigate staggering effects in detail, as a function of both Z and N.

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