Even-odd effects in Z and N distributions of fragments emitted at intermediate energies

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Even-odd effects in Z and N distributions of light fragments emitted at forward angles in nuclear collisions ^{40}Ca + ^{40}Ca, ^{40}Ca + ^{48}Ca, and ^{48}Ca + ^{48}Ca at 25 MeV/nucleon and identified in charge and mass with the Chimera multidetector have been analyzed. The amplitude of even-odd staggering effects seems to be related to the neutron to proton ratio N/Z of the entrance channels. A qualitative explanation of this effect, taking into account the deexcitation phase of primary excited fragments, is discussed.

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I. INTRODUCTION

For a long time, it has been pointed out that the emission of light fragments in nuclear reactions at low, intermediate, and high bombarding energies shows structure effects [1]. In particular, Z (proton number) distributions of light fragments emitted in heavy-ion collisions from ≈10 to ≈1000 MeV/nucleon often reveal even-odd staggering effects, i.e., even Z fragments are emitted with a slightly higher probability compared to the odd Z ones [2–14]. Curiously, a similar behavior can be also observed in charge distributions involving the relative elemental yields of nuclear abundances in the solar system [16] and in cosmic ray nuclear composition [17]. It is, in general, difficult to find in the literature N (neutron number) distributions of light fragments [15]. An example is discussed in Ref. [2] for low-energy deep-inelastic collisions; even in this case an even-odd staggering effect has been seen.

A simple (and qualitative) explanation of this phenomenon can be obtained by considering the effect of nuclear pairing forces. They can explain the subtle differences in the mass of nuclei with odd or even numbers of protons or neutrons [18]. They have also an important role in the determination of one-particle emission threshold distributions [19]. This last point is an important aspect in the case of nuclear reactions well over barrier, where the production of highly excited fragments is observed. Such fragments deexcite mainly by particle emission, until their excitation energy reaches the particle-emission threshold; at lower excitation energy, they can only deexcite by γ-ray emission [1]. For this reason, one-neutron and one-proton separation energy distributions of light fragments play an important role in the determination of Z (or N) distributions of final (detected) fragments [9]. One-proton (or one-neutron) separation energies for even Z (or N) are higher than the odd-Z (or N) case due to the effect of pairing forces. For this reason, it is more difficult for an even-Z (or N) fragment to deexcite by particle emission during the last steps of the deexcitation cascade. This fact could qualitatively explain the even-odd effect in Z or N fragment distributions. Obviously, for a more detailed interpretation of this phenomenon, one must also take into account the different reaction mechanisms involved in the collisions [10].

Another key quantity governing the deexcitation pattern of hot fragments is their neutron to proton ratio N/Z. It has been shown in the literature that the amplitude of even-odd oscillations characterizing the *charge distributions* of light fragments are more and more softened when the N/Z of entrance channels increases [5–11,20,21]. This effect has been explained by considering that, in contrast to $N \approx Z$ collisions, in neutron-rich collisions, neutron-rich isotopes of odd-Z fragments can be populated with larger probability; this effect contributes to smooth the even-odd oscillations seen in the Z distribution of fragments emitted by neutron-rich systems [7,11].

In this work we show and discuss results of even-odd effects on Z and N distributions of light fragments emitted in nuclear collisions by using Ca isotopes as beams and targets, i.e., ^{40}Ca + ^{40}Ca, ^{40}Ca + ^{48}Ca and ^{48}Ca + ^{48}Ca collisions at 25 MeV/nucleon. In this way, the role played by the neutron richness of the entrance channel on light fragment distributions can be deeply investigated. We observe that the staggering on Z distributions is enhanced for systems with a low N/Z

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ratio, while the staggering on N distributions is enhanced for high-N/Z systems. A qualitative explanation for these effects is discussed.

II. EXPERIMENTAL APPARATUS

The experiment was performed at the Laboratori Nazionali del Sud (LNS-INFN) by using beams of ^{40,48}Ca at 25 MeV/nucleon, accelerated by the Superconducting Cyclotron, impinging on self-supporting, isotopically enriched ^{40}Ca (1.24 mg/cm^2) and ^{48}Ca (2.7 mg/cm^2) targets. The reaction products were detected by using the 4π Chimera detector [22]. The device is constituted by 1192 Si-CsI(Tl) telescopes, covering $\simeq$94% of the whole solid angle. The average thickness of Si detectors is 300 μm, while CsI(Tl) thicknesses vary as a function of the polar angle. More details about the array and its detection and identification characteristics are discussed in Refs. [23,24]. We analyzed only well-reconstructed events, i.e., events where the total detected charge was between 80% and 100% of the total charge in the entrance channels, $Z_{\rm tot} = 40$. Very peripheral quasielastic reactions were removed during the experiment by the chosen electronic trigger condition, requiring the detection of at least three charged particles with $Z > 1$.

Figure 1 shows an example of charge and mass identification obtained by using the $\Delta E - E_{\rm res}$ technique for a well-performing telescope of the Chimera array. In order to obtain good-quality N distributions, we include in the analysis only telescopes with an isotopic resolution similar to that of

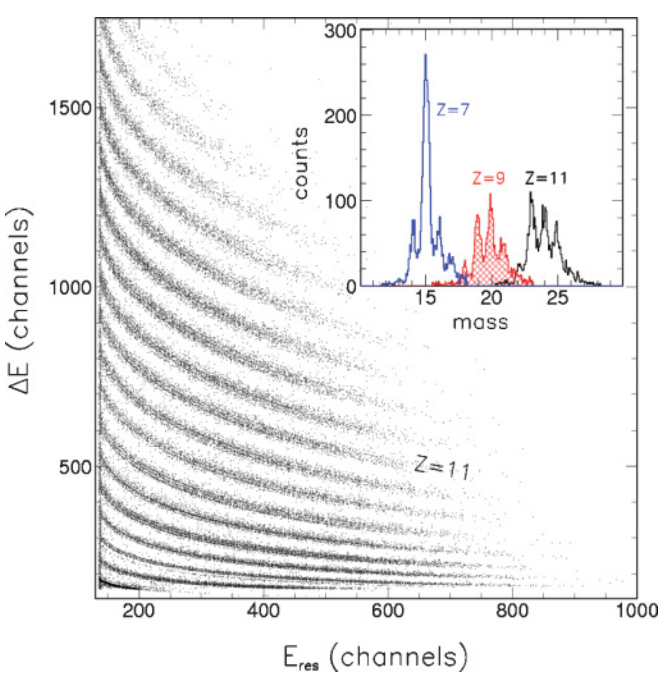

FIG. 1. (Color online) $\Delta E - E_{\rm res}$ scatterplot for a well-performing telescopes (polar angle $\theta_{\rm lab} = 10.8^\circ$) of the Chimera array obtained during the ^{48}Ca + ^{48}Ca reaction at 25 MeV/nucleon. In the inset, mass distributions obtained for N, F, and Na isotopes ($Z = 7, 9, 11$) are plotted to show the quality of isotopic identification.

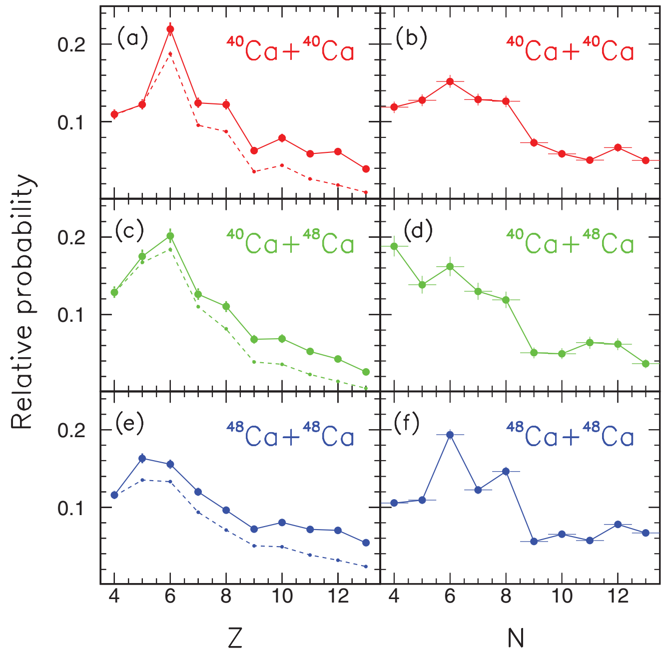

FIG. 2. (Color online) (a), (c) and (e) Experimental Z distributions of light fragments emitted at $10^\circ < \theta_{\rm lab} < 13^\circ$ (solid lines with large circles) in the ^{40}Ca + ^{40}Ca, ^{40}Ca + ^{48}Ca, and ^{48}Ca + ^{48}Ca reactions, respectively. These distributions have been normalized to the total number of fragments emitted having $4 \leqslant Z \leqslant 13$. Dashed lines show fragments emitted at $13^\circ < \theta_{\rm lab} < 20^\circ$. In this case, for clarity reasons, data have been normalized to match the $Z = 4$ point of the distribution at forward angles. (b), (d), and (f) Experimental N distributions of light fragments emitted at $10^\circ < \theta_{\rm lab} < 13^\circ$ (solid lines with large circles) in the ^{40}Ca + ^{40}Ca, ^{40}Ca + ^{48}Ca, ^{48}Ca + ^{48}Ca reactions, respectively. Vertical errors are statistical. Horizontal error bars are related to the identification resolution of the selected detectors.

Fig. 1 (while for Z distributions a larger number of telescopes can be used). Isotopic lines can be resolved up to aluminium isotopes. In the inset of Fig. 1, reconstructed mass spectra for nitrogen, fluorine, and sodium isotopes are plotted in order to show the identification quality and to get an idea of the collected statistics for each telescope.

III. EVEN-ODD EFFECTS ON Z AND N FRAGMENT DISTRIBUTIONS

Figures 2(a)–2(f) show (solid lines with large circles) the relative emission yields of light fragments as a function of their proton and neutron numbers emitted at a mean polar angle $\overline{\theta_{\rm lab}} = 11.5^\circ$; fragments are isotopically identified by using the $\Delta E - E_{\rm res}$ technique. By comparing the various panels in Fig. 2 one can observe that the amplitude of the even-odd oscillation of the relative emission yield is quite different in the three studied systems. Moreover, Z and N distributions show specular behavior. In more detail, for Z distributions [Figs. 2(a), 2(c), and 2(e)] a rather large amplitude of the even-odd staggering effect is seen for the $N = Z$ system ^{40}Ca + ^{40}Ca, while the same effect is smoothed in the more-neutron-rich systems ^{40}Ca + ^{48}Ca and ^{48}Ca + ^{48}Ca. Instead, by looking at N distributions of emitted light fragments, we observe a reversed behavior: the larger oscillations of the N distribution are observed in the more-neutron-rich system ^{48}Ca + ^{48}Ca, while for the N distribution obtained in the ^{40}Ca + ^{40}Ca system they are less pronounced. In Z distributions we can see a local minimum for $Z = 4$ isotopes (beryllium production). This may be qualitatively explained by considering the special characteristics of beryllium isotopes; it is well known, in fact, that ^{8}Be is unbound, while ^{9}Be is characterized by a rather small one-neutron separation energy ($S_{1n} = 1.66$ MeV). These structure effects reduce the probability to observe a beryllium isotope in the final stage of a deexcitation chain. Similar conclusions can be drawn for the local depletion of fluorine ($Z = 9$) isotopes in Z distributions. On the contrary, for ^{40}Ca + ^{40,48}Ca systems, carbon emission is enhanced; probably it is due to the quite high one-proton separation energy of $^{11-14}$C isotopes due to shell-closure effects. Similar conclusions can be found in the literature [6,11]. It is interesting to note that even at more backward angles ($13^\circ < \theta_{\rm lab} < 20^\circ$), the Z distributions of light fragments (dashed lines in Fig. 2) show even-odd staggering effects similar to those observed at forward angles. We note that, mainly due to the reaction kinematics, the emission of large mass fragments is slightly more suppressed. For clarity reasons, these yields have been normalized to the $Z = 4$ point of $\overline{\theta_{\rm lab}} = 11.5^\circ$ distributions.

In order to give a quantitative estimation of the even-odd effect on Z and N distributions of light fragments, we performed a simple analysis of the experimental elemental yields at forward angles ($\overline{\theta_{\rm lab}} = 11.5^\circ$). We first fitted the experimental Z and N distributions, shown in Fig. 2 (solid lines), with fourth-degree polynomials in order to reproduce the mean behavior of the distributions. Then we calculated, point by point, the normalized square deviation of experimental data with respect to the polynomial fit, summed over all the points of Z or N distributions:

$$S = \frac{1}{\mathcal{N}} \sum_i \frac{[y_{\rm exp}(i) - y_{\rm fit}(i)]^2}{[y_{\rm fit}(i)]^2}. \quad (1)$$

Here $y_{\rm exp}(i)$ is the experimental relative yield of the ith element (isotope or isotone), and $\mathcal{N}$ is the number of elements of the distribution considered in the calculation. $y_{\rm fit}(i)$ is the yield of the ith element (isotope or isotone) as obtained from the polynomial fit of the mean behavior of the distribution. In Fig. 3 we plot the S value as a function of the N/Z ratio of the total system for the investigated reactions. The correlation between the oscillations due to even-odd effects (expressed by means of the quantity S) and the N/Z of the total systems is evident and underlines the role played by the N/Z degree of freedom to explain subtle effects in the yield distributions of isotopes and isotones in intermediate-energy heavy-ion collisions.

As already discussed, these effects could be qualitatively interpreted by considering that, in neutron-rich nuclear reactions, light clusters with an excess of neutrons are more likely to be emitted, while in neutron-poor reactions, neutron-poor fragments are more easily produced. Neutron-rich excited fragments deexcite mainly by emitting neutrons, while the neutron-poor ones deexcite more easily by emitting protons.

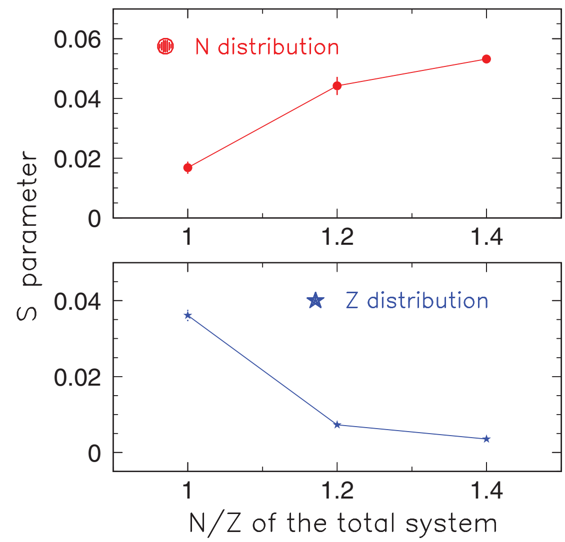

FIG. 3. (Color online) Correlation between the staggering parameter S (defined in the text) observed in the experimental *Z distributions* (blue stars) and *N distributions* (red circles) at $10^\circ < \theta_{\rm lab} < 13^\circ$ as a function of the N/Z of the total systems populated in ^{40}Ca + ^{40}Ca, ^{40}Ca + ^{48}Ca, and ^{48}Ca + ^{48}Ca reactions. Lines are only to guide the eye.

For this reason, in *neutron-poor* systems (for example, ^{40}Ca + ^{40}Ca), the final Z distribution of emitted light fragments should reflect even-odd oscillations characterizing the *one-proton* separation energy distribution of light nuclei near the stability valley.

As expected from symmetry considerations, for neutron-rich systems (for example, ^{48}Ca + ^{48}Ca), the deexcitation cascade would involve mainly neutron emissions; in such a way, the final *neutron* distribution of light fragments would be related to even-odd oscillations characterizing *one-neutron* separation energy distributions of light nuclei.

It is difficult to obtain quantitative theoretical predictions of the amplitude of the staggering effect here discussed; they could be obtained starting with dynamical calculations [25,26], followed by accurate statistical calculations [27–29] of the deexcitation phase of excited fragments. It has been also recently pointed out [30] that the strength of symmetry energy could play a slight role in the amplitude of even-odd effects. Due to uncertainties both on dynamical and statistical calculations, it is, in general, difficult to obtain model-independent predictions on the role played by the symmetry potential on the amplitude of even-odd staggering effects. We plan to explore this topic in future investigations.

Finally, we underline another result that can be deduced from Fig. 3. It shows, in fact, that in the energy regime of 25 MeV/nucleon bombarding energy, the multiplicity of preequilibrium emitted nucleons does not destroy the memory of the N/Z of the entrance channel. We explored this aspect by performing COMD-II calculations [31–33] for the three studied systems; after the preequilibrium emission, the emitting sources maintain a memory of the initial N/Z content. In this respect, it will be interesting to study even-odd oscillations in fragment distributions obtained by colliding systems very far from stability at the recently developed radioactive ion beam facilities.

IV. CONCLUSIONS

In conclusion, we analyzed the emission of isotopically resolved light fragments in ^{40}Ca + ^{40}Ca, ^{40}Ca + ^{48}Ca, and ^{48}Ca + ^{48}Ca reactions at 25 MeV/nucleon. Even-odd effects on charge and neutron distributions of light fragments have been observed; in particular, even-Z or even-N fragments are, in general, more likely to be emitted. Moreover, the amplitude of the even-odd effect on Z and N distributions seems to be related to the neutron to proton ratio N/Z of the entrance channel. We discuss a qualitative explanation of this effect by considering the influence of the N/Z on the deexcitation phase of the primary excited fragments.

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