Staggering in S+Ni collisions

L. Morelli[1], M. D'Agostino[1], M. Bruno[1], F. Gulminelli[2], , G. Baiocco[1], S. Barlini[3], L. Bardelli[3], F. Cannata[1], G. Casini[3], E. Geraci[4], F. Gramegna[5], V. L. Kravchuk[5], T. Marchi[5,6], A. Moroni[7], A. Ordine[8], Ad. R. Raduta[9]

[1] *Dipartimento di Fisica dell'Universita' and INFN, Bologna, Italy.*
[2] *LPC (IN2P3-CNRS/Ensicaen et Universite', F-14076 Caen cedex, France.* [3] *INFN, Firenze, Italy.*
[4] *Dipartimento di Fisica dell'Universit`a and INFN,* [5] *INFN, Laboratori Nazionali di Legnaro, Italy Catania, Italy.*
[6] *Dipartimento di Fisica dell'Universit`a, Padova,Italy.* [7] *INFN, Milano, Italy.* [8] *INFN, Napoli, Italy.*
[9] *NIPNE,Bucharest-Magurele, POB-MG6, Romania.*

INTRODUCTION

Odd-even effects in fragment production have been studied since a long time and never quantitatively understood. The odd-even anomaly was reported in the literature [1,2] to be more pronounced in reactions involving Ni projectile and targets, in particular in n-poor systems. In some experiments [1,2] the magnitude of the odd-even effect is found to be related to the isospin of the projectile and/or the target. The effect in final observables was observed to be very large in reactions where at least one of the reaction partner has N − Z = 0 (as ^{32}S). From a theoretical point of view, odd-even effects in fragmentation reactions are clearly linked to the pairing residual interaction and its dependence on temperature, which are very important quantities both in nuclear physics [3] and in nuclear astrophysics [4].

EXPERIMENT AND DATA SELECTION

The measurements were performed in the third experimental hall at the Legnaro National Laboratory.
A pulsed beam (around 1 ns FWHM) of ^{32}S provided by the TANDEM-ALPI acceleration system was used to bombard self-supporting ^{58}Ni and ^{64}Ni targets, 150 μg/cm^2 thick. The bombarding energy was 463 MeV.The detecting device is composed by the GARFIELD detector [5] covering almost completely the angular polar range from 30^o to 85^o and an annular three-stage detector (Ring Counter) [7] covering laboratory forward angles from 5.3^o to 17.5^o. GARFIELD is made by a drift chamber, filled with CF_4 gas at low pressure (53 mbar), azimuthally divided into 24 sectors, each one consisting of 8 ΔE −E telescopes, for a total of 96 telescopes. The operation of the GARFIELD apparatus largely bases on the ΔE −E technique, in which the ΔE signal is given by the drift chamber. The CsI(Tl) scintillation detectors, lodged in the same gas volume, are used to get information on the residual energy. The Ring Counter [6] is an array of three-stage telescopes realized in a truncated cone shape. The first stage is an ionization chamber (IC), the second a 300μm strip silicon detector (Si) and the last stage a CsI(Tl) scintillator. The RCo has eight separate silicon detectors, pie shaped, each one segmented into eight independent annular strips on the front surface (junction side). To sort the measured events as a function of the centrality, we adopted the method of *shape analysis* [7],

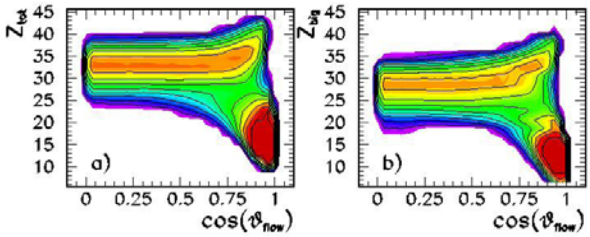


Fig. 1. Total detected charge and charge of the largest fragment as a function of the cosinus of the flow angle for ^{32}S+^{58} Ni under the condition: $P_z/P_{beam} \geq 0.5$.

common to other intermediate and high energy experiments performed with ≅ 4π detectors [8,9].
In Fig. 1 we examine the behavior of the total detected charge as a function of the "flow angle" [7] for the n-poor system. The behavior is the same for the n-rich one. The flow angle was calculated for events where at least a fragment (Z ≥ 3) and an α-particle have been detected. We observe in Fig. 1 that peripheral events, characterized by a total detected charge close to the projectile charge, keep a strong memory of the entrance channel and are therefore restricted to low value of the flow angle. Higher values of the total charge are distributed over the whole range of θ_{flow} with nearly constant statistics, which implies a nearly flat distribution of cos(θ_{flow}), as expected for spherical events. From now on, *central* events will be defined by the additional condition of a total detected charge $Z_{tot} \geq 70\% \cdot Z_{S+Ni}$, and *peripheral* events by Ztot ≤ 25 and $\theta_{flow} \leq 40^o$.

RESULTS

Figure 2 displays the fragment (Z ≥ 3) charge distribution measured for the two reactions in central (left) and peripheral (right) events. The superposition of the two peripheral data sets shows that our selection of peripheral events is effective in isolating the contribution of the quasi-projectile, and that the contribution from dynamical neck-like fragments does not considerably affect these integrated observables. A different behavior is observed in central collision, where the charge distribution does not scale with the size of the system and a clear isospin effect can be seen, similar to other experimental results [10] .
As far as staggering is concerned, we can see that for both reactions a well pronounced odd-even effect is seen in the charge distribution of peripheral collisions, while almost no staggering is apparent neither in the IMF yield (coming mainly from fusion-multifragmentation) nor in the residue

region (coming from fusion-evaporation) for central collisions, where only an extra-production of Carbon fragments is evident. This behavior has already been observed in many other reactions at low and intermediate incident energies, for central collisions [11,12].

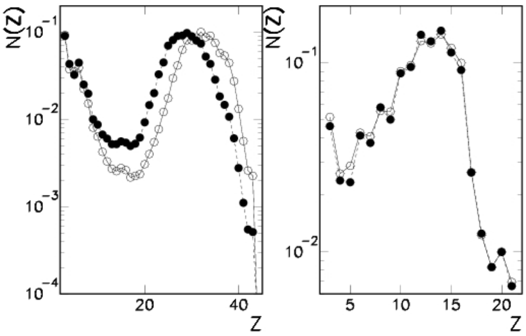


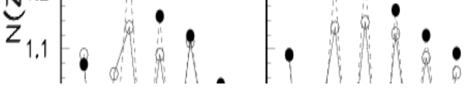
Fig. 2. Elemental fragment (Z≥3) distribution for $^{32}S+^{58}Ni$ (full symbols, dashed line) and $^{32}S+^{64}Ni$ (open symbols, full line) in peripheral sample

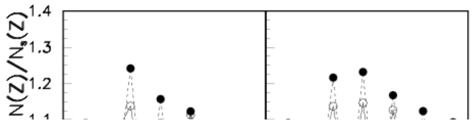
In almost all the experiments quoted in Ref.s [1,2] the samples correspond mostly to peripheral collisions or to fission-fragment charge distributions. To our knowledge, no staggering has been directly observed in charge distributions for carefully selected central collisions. Odd-even effects appear looking at the ratio of the charge distribution of a neutron-poor reaction and a neutron-rich one [12]. In this way, however, the absolute value of the even-odd staggering for each reaction is lost.

The difference observed between central and peripheral collisions could be ascribed to the isotopic ratio of the evaporating source, which is sensibly more neutron rich for the fused sources than for the quasi-projectile. However another important difference between the two samples concerns the excitation energy, 3 AMeV in average in the central sample and less than half of this value for the peripheral sample. This difference could lead to different mechanisms for fragment production.

To reinforce this conclusion, we show in Fig. 3 the ratio between the elemental charge distribution of the whole central sample and a smoothed distribution obtained by a parabolic interpolation of the measured yields over 5 consecutive points. By looking at Fig.3 it is evident that the staggering is present also in central collisions with amplitudes similar to the peripheral ones. Some extra differences between the two samples appear in this representation: the extra-production of Carbon with respect to oscillations of neighboring charges is larger in central collisions and the amplitude of the staggering decreases for increasing fragment charge, at difference with peripheral events, where it remains almost constant.

For the two centrality selections the different isospin of the entrance channel plays a minor role, enforcing the idea that a different mechanism of decay is at the origin of the observed differences between central and peripheral collisions. Specifically, only if the production yield as a function of the fragment size is reasonably constant a clear staggering





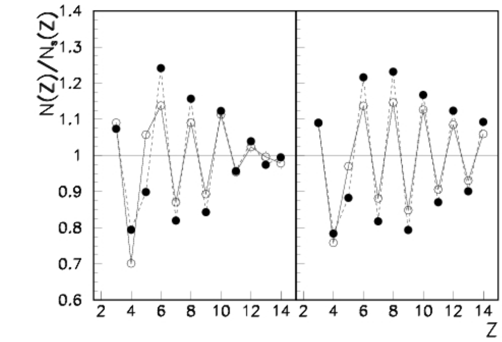


Fig. 3. Ratio of the elemental fragment (Z ≥ 3) distribution of Fig.2 for $^{32}S+^{58}Ni$ (full symbols connected by dashed lines) and $^{32}S+^{64}Ni$ (open symbols connected by full lines) by smoothed distributions obtained by a parabolic interpolation over 5 consecutive points. Left: central events. Right: peripheral collisions. Lines are drawn to guide the eye.

To investigate in more detail the influence of the excitation energy of the fragment source in central collisions, a possible way would be to analyze data in excitation energy bins, but the statistics of the present data-set is not sufficient.

The staggering effects appears to be a universal feature of fragment production, slightly enhanced when the emission source is neutron poor. A closer look at the behavior of isotopic chains reveals that odd-even effects cannot be explained by pairing effects in the nuclear mass alone, but depend in a more complex way on the de-excitation chain. More detailed analyses are in progress [13], including comparisons with statistical models.

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