An Interpretation of Staggering Effects by Correlation Observables


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INTRODUCTION

Experimental studies of odd-even effects in fragment production have been performed since a long time. Recent experiments performed with 4π detectors have added experimental information on these anomalies [1–4]. However all these results have not produced clear-cut conclusions about their interpretation. A priori, these effects point to the pairing residual interaction and its dependence on temperature. Understanding the origin of odd-even effects is relevant for studies on symmetry energy, which can be linked to the isotopic distributions if these latter are not too much perturbed by secondary decays [5]. In a recent paper [3], we have reported on an experimental study of staggering in S + Ni collisions at 14.5 A MeV. Important odd-even effects have been observed in peripheral and central collisions. A detailed study of the most probable decays contributing to the yield of the different isotopic chains has additionally indicated that the lowest emission threshold for particle production cannot be the unique factor governing the staggering. To quantitatively control the population at the last-but-one evaporation step, we present here an experimental estimate of secondary evaporation using a correlation function based technique.

EXPERIMENTAL DISTRIBUTIONS

The reactions $^{32}$S+$^{58,64}$Ni at 14.5 A MeV were measured at the TANDEM-ALPI acceleration system of the Legnaro National Laboratory, with the high acceptance detecting device GARFIELD coupled to an annular three-stage detector (Ring Counter) [6, 7]. The sorting of the measured events as a function of the centrality has been performed with the method of the “shape analysis” [3]. A comparison to the GEMINI evaporation code suggests that peripheral events are associated to the evaporation from a quasi-projectile source with $< E^* > \approx 1$ A MeV, $< Z > \approx 16$, $< A > \approx 32$, and an angular momentum $J = 0 \div 16 \hbar$. Odd-even effects in the elemental fragment charge distribution are clearly established (see fig. 1) and can be highlighted by the ratio of the measured distribution and its smoothing, obtained by a parabolic interpolation of the measured yields over 5 consecutive points. Considering that for almost all the isotopically resolved yields ($Z \leq 8$) the most abundant isotope of each element is $N = Z$, the observed staggering can be interpreted as dominance of even-even isotopes over odd-odd ones. This can be easily understood [2] from the pairing contribution to the isotope masses, if the last evaporation step corresponds to nucleon emission. However, since for the $N = Z$ isotopes the lowest emission threshold typically corresponds to $\alpha$ decay and the $\alpha$ separation energy shows a smooth behavior as a function of the charge, the extra yield of even-even isotopes is not explained by the energy balance of the last evaporation step.

WARM FRAGMENTS

For a quantitative understanding of odd-even effects we propose a back-tracing technique based on correlation functions of the relative kinetic energy of isotope pairs. If we concentrate on light nuclei ($3 \lesssim Z \leq 8$), their discrete spectrum is so extended that the last particle evaporation step takes place typically from a discrete resonance, which can at least in principle be recognized as a peak in a relative kinetic energy two-body correlation function. Experimentally the two-particle correlation function is defined as:

$$
\sum_{(\vec{p}_1,\vec{p}_2)} Y_{12}(\vec{p}_1,\vec{p}_2) = C \left[ 1 + R(E_{rel}) \right] \sum_{(\vec{p}_1,\vec{p}_2)} Y_1(\vec{p}_1) Y_2(\vec{p}_2)
$$

where $Y_{12}$ is the two-particle coincidence yield of a given pair of particles with momenta $\vec{p}_1$ and $\vec{p}_2$, and the $Y_i(\vec{p}_i)$ are the single particle yields for two particles belonging to different events. The sumations of equation 1 run over pairs of momenta $\vec{p}_1$ and $\vec{p}_2$ corresponding to the
same bin in relative energy \( E_{\text{rel}} \). The correlation function describes how the correlation between interacting particles measured in the same event differs from the underlying two-particle phase space, modeled by the mixing event technique \[9\]. The constant \( C \) is the ratio of the total numbers of mixed and coincident pairs. To investigate the decay of particle unbound states one has to disentangle the long range Coulomb and short range nuclear contributions to the two particle phase space \( 1 + R(E_{\text{rel}}) = 1 + R_{\text{Coul}}(E_{\text{rel}}) + R_{\text{nuc}}(E_{\text{rel}}) \); then perform a fit of the measured correlations, by empirically parametrizing the Coulomb contribution \[9\]:

\[
R_{\text{nuc}}(E_{\text{rel}}) = \frac{e^{-E_{\text{rel}}/T_{\text{eff}}}}{h^3/4\pi\sqrt{2m_{\text{eff}}}} \sum_{i} \frac{(2J_i + 1)\Gamma_i/2(B.R.)}{(E_{\text{rel}} - E_i^*)^2 + \Gamma_i^2/4}
\]  

where \( S_1 \) and \( S_2 \) are the spins of the considered particles, \( \mu \) is their reduced mass, \( V_f \) the effective emitting source volume, \( T_{\text{eff}} \) the associated effective temperature, \( J_i, E_i^*, \Gamma_i \) the spin, excitation energy and width of the level \( i \), and \( (B.R.) \) is the branching ratio for decay to the measured channel. The free parameters of the fit are the Coulomb parameters \( E_c \), \( \gamma \) and \( V_f \), \( T_{\text{eff}} \), which would represent a physical source volume and temperature only in the idealized situation of a single decay step of a fully equilibrated source. Only levels with spins, excitation energies, widths and branching ratios experimentally measured \[8\] were considered in the fit. We report in Fig. 2 the \( d - \alpha \) correlation function as an example of our analysis. More cases are reported in Ref. \[4\]. Primary yields, calculated by multiplying the nuclear contribution for the uncorrelated yield, \( Y_{\text{cor}}(E^*) = \left( R(E^*) - R_{\text{Coul}}(E^*) \right) \sum_k Y_k \) \[9\], are shown by symbols in the bottom panel of Fig. 2 together with the contributions from \( ^{6}Li^* \) excited levels entering in Eq. 2. The total primary population of a given isotope at the last-but-one evaporation step \( Y(A^*, Z^*) \) is calculated by numerically integrating the primary yields over the explored range of excitation energy.

To evaluate the fraction of the coincident pairs emitted by decay of particle unbound states one has to disentangle the long range Coulomb and short range nuclear contributions to the two particle phase space \( 1 + R(E_{\text{rel}}) = 1 + R_{\text{Coul}}(E_{\text{rel}}) + R_{\text{nuc}}(E_{\text{rel}}) \); then perform a fit of the measured correlations, by empirically parametrizing the Coulomb contribution \[9\]

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Fig. 2. Upper part: relative kinetic energy correlation function (symbols) of \( d - \alpha \) pairs, fitted through Eq. 2 (thick solid line). The Coulomb background (thick solid line) is indicated together with its uncertainties (dashed lines). Lower part: experimental population of primary \( ^{6}Li^* \) parents (symbols) and single excited states with its uncertainties (dashed lines) together with their sum (thick line) as a function of the excitation energy.

Fig. 3. Population of primary fragments (left) and their average excitation energy (right) for the \( ^{32}S + ^{58}Ni \) (full symbols and dashed lines) and \( ^{32}S + ^{64}Ni \) (circles and full lines) data set.

\[8\] www.nndc.bnl.gov/nudat2/