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Odd-even *Z* isospin anomaly in heavy-ion reactions

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Intermediate mass fragment (IMF) production is different for the reaction pair ^{58}Fe+^{58}Fe and ^{58}Ni+^{58}Ni for which the only difference is the ratio N/Z, 1.23 for ^{58}Fe and 1.07 for ^{58}Ni. For beam-velocity fragments at 5.4° with Z from 3 to 15 the more proton-rich Ni reaction produces more even-Z IMFs than the Fe reaction. The ratio (number of IMFs from ^{58}Ni+^{58}Ni)/(number of IMFs from ^{58}Fe+^{58}Fe) as a function of Z is about 10% larger for even-Z values than for odd-Z values. The magnitude of this odd-even effect is about the same for beam energies with $E/A=45$, 75, and 105 MeV. [S0556-2813(99)50509-8]

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When excited heavy nuclear systems break up, the yield of even-Z products often exceeds the yield of the adjacent odd-Z products. This odd-even effect is, however, not universal and is not well understood. We list here some of the situations in which the effect is seen and some in which it is not seen.

The odd-even effect has been observed in fission [1,2], in low-energy heavy-ion reactions (^{35}Cl+^{24}Mg at $E/A=8$ MeV) [3], and in the breakup of GeV/nucleon heavy projectiles [4–7]. Zeitlin *et al.* [4] find an enhancement for even-Z projectile-like fragments from 1.05A GeV ^{56}Fe on a variety of targets from hydrogen to lead. The magnitude of the effect does not depend on the target mass. Cummings *et al.* [5] and Webber *et al.* [6] report similar results. For some of the high energy studies the magnitude of the odd-even effect is found to be related to isospin. Knott *et al.* [7] find large odd-even effects for ^{40}Ca on liquid hydrogen at $E/A=357$ to 763 MeV and similar large effects with $T_z=0$ beams of ^{32}S and ^{36}Ar. For the $T_z=-2$ beams, ^{40}Ar and ^{52}Cr, the effect is smaller, about the same as Zeitlin *et al.* [4] found for $T_z=-2$ ^{56}Fe. For $T_z=-1$ ^{58}Ni the odd-even effect is intermediate when compared to $T_z=0$ and -2 beams. Data by Yennello *et al.* [8] show the effect in the breakup of Ag by ^{3}He at energies of 0.9 and 3.6 GeV for IMFs with $Z=3$ to 11. They find the excess of even-Z values to increase with energy. Within the accuracy of their data the odd-even effect is independent of the angle of the detector. The odd-even effect is also found for ^{58}Fe+^{58}Ni at 30A MeV for IMFs at 11° and the results compared with models [9]. No odd-even effect is seen at 40°. Raduta and Raduta [10] fit ^{40}Ar+^{45}Sc at $E/A=35$ to 115 MeV with a statistical model that includes level densities and binding energies. Their calculations show a small, energy-independent odd-even effect. Their overall fit to the data is good, although the accuracy of the data [11] is not good enough to show an odd-even effect.

No odd-even effect is seen for ^{40}Ca+^{40}Ca at $E/A=35$ MeV [12] in either projectile-like fragments or intermediate-velocity fragments. This is surprising because ^{40}Ca has $T=0$ and the energy is in the range for which a strong effect is seen in the mass 58 reactions. The effect is also not seen in the projectile fragmentation of ^{129}Xe at 790A MeV for Z values near 50 [13] or in central ^{84}Kr+^{197}Au collisions at $E/A=35$ to 400 MeV [14].

To explore more fully this odd-even effect and its possible relationship to isospin we have measured the yields of IMFs for two sets of reaction pairs ^{58}Fe+^{58}Fe and ^{58}Ni+^{58}Ni. These differ only in the values of the ratio N/Z, 1.23 for ^{58}Fe and 1.07 for ^{58}Ni. The experiment measures the final products from the decay of the excited projectile fragments. We will show that these products exhibit an odd-even effect for both reactions, at a magnitude similar to that found in Ref. [9]. In this work, however, we extend the study to a comparison of the ratio of the yields for the two N/Z systems. For each Z we measure the ratio of the yield of fragments from the Ni projectile to the yield of fragments from the Fe projectile. These measurements provide new and interesting results.

Beams of ^{58}Ni and ^{58}Fe at $E/A=45$, 75, and 105 MeV from the K1200 cyclotron at the National Superconducting Cyclotron Laboratory were focused onto isotopically pure ^{58}Ni and ^{58}Fe targets at the center of the Michigan State University 4π Array [15]. The 4π Array measures charged particles over most of the sphere. For this analysis, data from the entire Array is used for determining impact parameters. The IMFs discussed here were measured in a ring of ten phoswich detectors that completely covered the laboratory angles from approximately 3° to 8° (centered at 5.4°). The threshold energies of the detectors ranged from 100 MeV for Li to 1080 MeV for P ($Z=15$). Additional experimental detail is given in Ref. [16] which made use of the same data.

Figure 1 shows IMF energy spectra for $Z=3$ to 9 from an

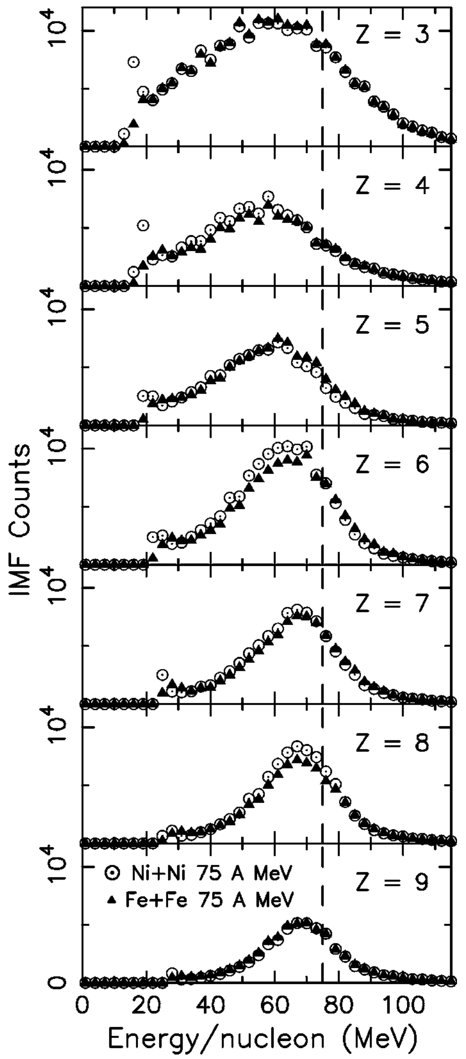

FIG. 1. IMF energy spectra at 5.4° for 75*A* MeV ^{58}Ni+^{58}Ni and ^{58}Fe+^{58}Fe. Beam velocity fragments have energy 75*A* MeV, dashed line.

equal number (14×10^6) of Ni and Fe events for a beam energy of 75*A* MeV. To exclude most IMFs that are not spectator fragments the impact parameter is required to be between 1/3 to 2/3 of the maximum value. The impact parameter is assumed to be inversely correlated to the transverse energy of the light charged particles ($Z=1$ and 2). Leaving the IMFs out of the transverse energy calculation helps suppress autocorrelations. The kinetic energy spectra in Fig. 1 show peaks corresponding to velocities slightly less than the beam velocity—as is expected for spectator fragments. For $Z=10$ to 15 the spectra are similar to those for $A=7$ to 9. The fluctuations for the smaller Z values are the result of aliasing in the conversion of fragment energy to E/A. The statistical uncertainties are smaller than the symbols. There are systematic errors caused by uncertainty in the Z separation for individual detectors.

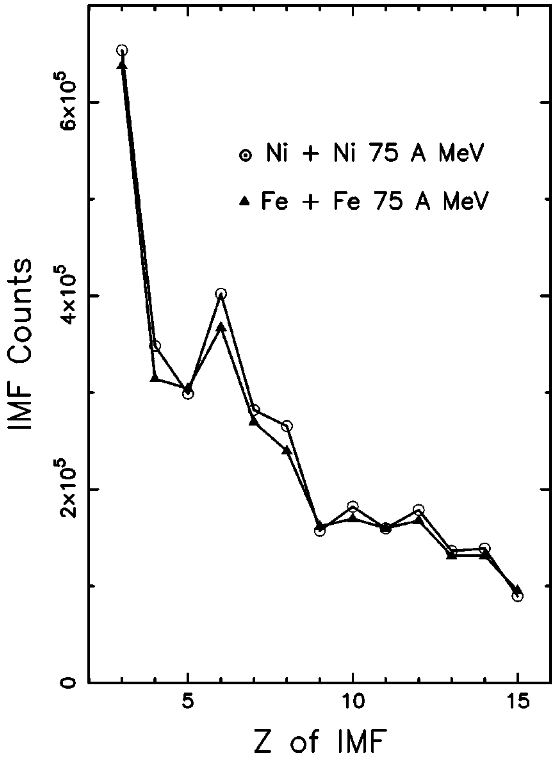

FIG. 2. Number of IMFs as a function of *Z* for ^{58}Ni+^{58}Ni and ^{58}Fe+^{58}Fe obtained by integrating the energy spectra starting at 30*A* MeV (see Fig. 1).

The larger number of even-*Z* fragments from ^{58}Ni+^{58}Ni can be seen in Fig. 1, but the odd-even effect for both reactions and the larger effect for Ni is shown more clearly by summing the energy spectra, Fig. 2. To avoid uncertainties related to the low energy cutoff of the detectors, the sums are started at 30*A* MeV.

The excess of even-*Z* IMFs can be quantified using a formula developed as part of similar studies of fission fragments. The quantity δ in Eq. (1) [17,1] is a measure of the local (with respect to Z) odd-even effect using third differences [1]. Each point in Fig. 3 represents the magnitude of the odd-even effect for four consecutive Z values, centered at $Z+\frac{3}{2}$:

$$\delta(Z)=\frac{1}{8}(-1)^{Z+1}\{\ln Y(Z+3)-\ln Y(Z)\\ -3[\ln Y(Z+2)-\ln Y(Z+1)]\}. \qquad (1)$$

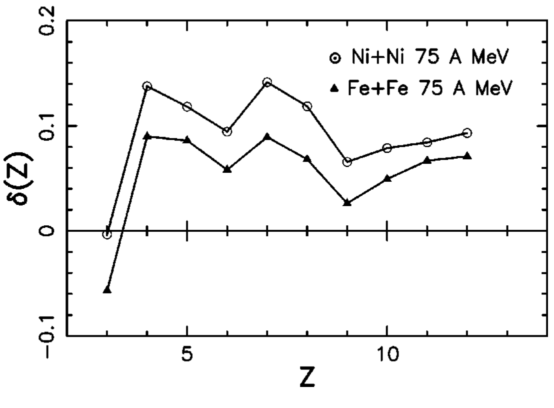

FIG. 3. Excess of even-*Z* over odd-*Z* fragments as a function of *Z* calculated from the data shown in Fig. 2. $\delta(Z)$ is defined in Eq. (1).

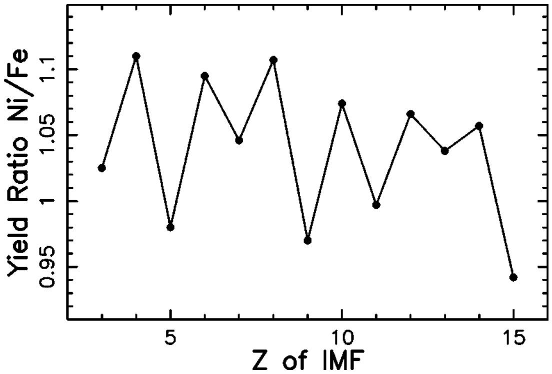

FIG. 4. Yield ratios of beam-velocity fragments as a function of *Z* for 75*A* MeV ^{58}Ni+^{58}Ni and ^{58}Fe+^{58}Fe.

In this equation $Y(Z)$ are the yields for particular values of Z (the points in Fig. 2). A positive δ implies an excess of even-*Z* fragments relative to odd-*Z* fragments. The resulting δ values are plotted in Fig. 3. This figure shows an excess of even-*Z* fragments for both Ni and Fe with a larger excess for Ni. The negative δ for $Z=3$ is caused by the large cross section for making Li ($Z=3$) in the low energy part of the $E/A=30$ to 110 MeV range (see Fig. 1).

Figure 4 shows the ratio of the Ni points to the Fe points in Fig. 2. This is another way of showing that the odd-even effect is larger for Ni than for Fe. Although uncertainties become magnified in such a differential view of the data, the statistical uncertainties are still smaller than the symbols. Errors in separating the IMFs by *Z* could give larger errors to some of the points but not enough to eliminate the odd-even fluctuations that characterize the figure.

The magnitude of the ratio of the odd-even effect is independent of beam energy from $E/A=45$ to 105 MeV. Figure 3, showing δ vs *Z*, and Fig. 4 look about the same if they are replotted with data from either 45 or 105 *A* MeV. This constancy occurs in spite of the fact that the number of IMFs per event and the steepness of the yield as a function of *Z* both increase with beam energy. The systematic uncertainties are larger at 45 and 105 *A* MeV. At 45*A* MeV some of the spectator fragments have an energy below the threshold energy of the detector; at 105 MeV the *Z* resolution is less certain.

To examine a possible basis for the observed behavior we have performed a series of exploratory calculations using the model [18]. In this model, fragments are statistically emitted from an excited source which is allowed to expand under the opposing influences of thermal pressure and a restoring nuclear force. The rates of emission are determined by the properties of the emitted fragments and those of the source. These rates are provided by Weisskopf detailed-balance and are governed by the conditions of the source including entropy, energy, and density. The exact properties of the emitted fragments are included and the binding energy of the instantaneous source is characterized by a schematic liquid-drop description. The species to be emitted are provided by input files for each calculation. This flexibility of the model provides a means for testing the influences of different aspects of a reaction.

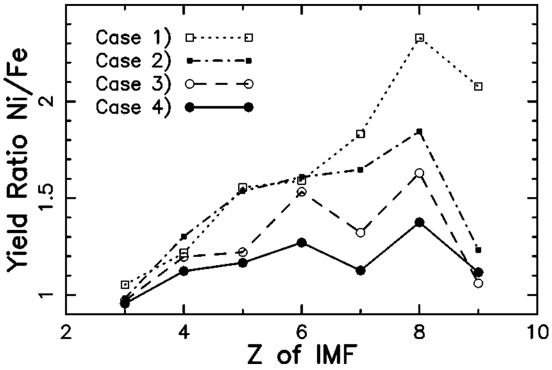

FIG. 5. Yield ratios as a function of *Z* for sources of ^{58}Ni and ^{58}Fe calculated for each of four classes of emitted fragments.

In general the yields of a given isotope depend on two general properties, binding energies and statistical weights. To explore these aspects separately we performed four separate classes of calculations, all for initial sources of ^{58}Ni and ^{58}Fe at initial excitation energies of 7.5*A* MeV. These calculations differed only by the fragments considered for emission with the following different cases studied: Case (1) included the bound ground states of isotopes up to $Z=9$, with the artificial assumption that each has zero spin, and thus equal statistical weights. This case tests the influence of binding energy alone. Case (2) includes the bound ground states of the previous case but with the proper spins and hence different degeneracy factors. Case (3) includes the same species as the previous two, but also includes the bound excited states of each species. Including these provides a change in the effective statistical weight for each isotope. Finally, in case (4) (the most complete case) we add the low-lying known resonances for each of the isotopes in addition to the bound states. After the primary yield is calculated the particle unstable decays are taken into consideration in providing the final yields.

The results of the predictions of these calculations for the ratio of yields by *Z*, for initial sources of ^{58}Ni relative to ^{58}Fe are shown in Fig. 5. With increasing completeness the general yields for Ni and Fe are brought closer to equality. i.e., the magnitudes of the ratios decrease toward unity. The odd-even oscillations develop when the bound-state statistical weights are added, and persist with the inclusion of the unbound resonances.

In all of the calculations the isotope distributions for each *Z* are biased toward the lighter masses for Ni and toward the heavier masses for the Fe initial sources. This is expected from the differences in the N/Z ratios. Two consequences of this biasing are seen in two aspects of the calculated ratios. First, the Ni yields are biased toward proton rich isotopes which have a greater probability for charged-particle decay. Hence for $Z=3$ and $Z=4$ this feature provides a relative downward shift in the calculated ratios for case (4). Before the charged-particle decay the odd-even fluctuations continue to $Z=3$ and $Z=4$ in a manner similar to that seen for the higher *Z* values.

Second, the neutron rich isotopes are numerous and readily populated. These provide substantial additional weight from neutron unstable resonances which do not alter

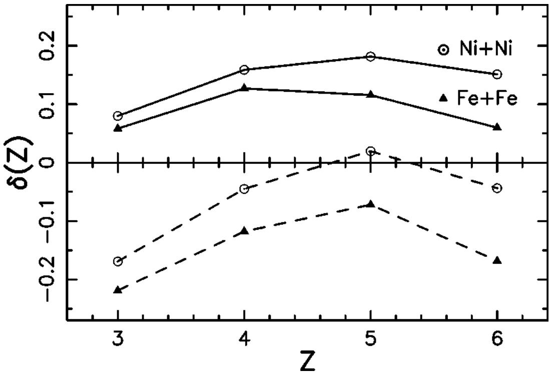

FIG. 6. Excess of even-*Z* over odd-*Z* fragments as a function of *Z* shown by $\delta(Z)$ as defined in Eq. (1). Solid lines are full calculations, case (4). Dashed lines are for bound states only, case (3).

the charge of the fragment. Thus the yield from the neutron rich Fe is increased relative to the Ni. This brings down the general scale of the ratios toward unity but does not greatly change the even-odd fluctuations. Since the number of proton rich isotopes above the most stable isotope varies with *Z*, this decay feature, i.e., charged-particle versus neutron, may be related to the general odd-even effect in each case separately.

Finally, values of $\delta(Z)$ were explored in the final two cases, (3) and (4). Here a surprising result was found as seen in Fig. 6. The values of $\delta(Z)$ for the most complete calculations are similar to the experimental results shown in Fig. 3, i.e., Fe and Ni have positive $\delta(Z)$ due to an enhancement of even-*Z* over odd-*Z* fragments, with Ni having the larger values. For the case including only the bound states, however, the values for $\delta(Z)$ are negative, reflecting the relative enhancement of odd-*Z* fragments [opposite to case (4)]. This difference occurs despite the fact that ratio of Ni yields to Fe yields for the two cases show a very similar odd-even effect. This observation suggests that the odd-even fluctuations in the ratio can be independent of the even-odd fluctuations in yields from a single type of source.

In summary, we have not only observed the odd-even effect in the yields of both sets of targets and projectiles, we have also found another odd-even effect in the ratio of the yields from the two different sources having different isospin, $^{58}\mathrm{Fe}+{}^{58}\mathrm{Fe}$ and $^{58}\mathrm{Ni}+{}^{58}\mathrm{Ni}$. The ratio of the number of fragments from the Ni reaction to the number from the Fe reaction is about 10% larger for even-*Z* fragments ($Z=3$ to 15). This 10% enhancement occurs for energies from 45 to 105 *A* MeV. The illustrative calculations suggest that this odd-even effect can be qualitatively explained in the context of statistical calculations. The results depend, however, on quite detailed aspects of the various emitted fragments, including the low energy density of bound and unbound states, their spin degeneracies, as well as simple systematic features of binding energy. In addition the results are also affected by the detailed bias in mass for each *Z*, which is strongly influenced by isospin of the source. There is some indication that the difference in the number of charged-particle unstable and neutron-unstable isotopes may contribute to both odd-even effects and may permit the isospin of the source to influence these effects.

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