A new order parameter for IMF isotope distributions

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An experiment was performed with beams of ^{64}Zn, ^{70}Zn and ^{64}Ni at 40 AMeV bombarding targets of ^{58}Ni, ^{64}Ni, ^{112}Sn, ^{124}Sn, ^{197}Au and ^{232}Th. Emphasis was placed upon obtaining high quality isotopic identification and high statistics for isotopes with Z between 3 and 18, for all the systems. Using a Si telescope, consisting of four quadrant Si detectors (129, 300, 1000 and 1000μm thick with area of 5cm x 5cm), isotopes of ^{6}LI to ^{9}Li, those of ^{7}Be to ^{12}Be and 6 to 8 isotopes for Z>4 were clearly separated and identified above an energy threshold ranging from 5 A MeV for Li isotopes to 10 A MeV for Si isotopes. In order to get the angle integrated yield of each isotope, the energy spectra observed at θ= 17.5°and 22.5° in different quadrants of the telescope were fit using a moving source parameterization.

From the Fisher model [1], the following relation is obtained between the yield of an isotope, Y, and physical constants;

$$Y = y_0 A^{-\tau} e^{-\beta \Delta\mu A}, \qquad (1)$$

Where y_0 is a normalization constant, τ is the exponent of the mass distribution, β is the inverse temperature and Δμ is the difference in chemical potential between neutrons and protons, i.e., the Gibbs free energy per particle, *F(I/A)*, near the critical point, where I=N-Z, is the difference between neutrons and protons in a given isotope. We can compare all systems on the same basis by normalizing the yields and factoring out the power law term. For this purpose we have chosen to normalize the yield data to the ^{12}C yield with τ =2.3, we define a ratio:

$$R = \frac{Y A^{\tau}}{Y(^{12}C)12^{\tau}}, \qquad (2)$$

In Figure (1) the quantity *F/T = - ln(R)/A* versus (I/A) is shown. I/A indicates the neutron to proton concentration in the emitting source. As one can see, the ratios for all isotopes are well distributed along a bell shaped function. This indicates that I/A, the neutron to proton concentration, is an good order parameter to govern the isotope distribution. All isotope yields measured in each reaction showed very similar distributions. The centroid of the distribution depends on the N/Z ratio of the reaction system, though the width is very similar from system to system.

An attempt was made to fit the distribution, using the Landau model [2,3]. In this approach the ratio of the free energy to the temperature is written in terms of an expansion:

$$\frac{F}{T} = \frac{1}{2}am^2 + \frac{1}{4}bm^4 + \frac{1}{6}cm^6 - m\frac{H}{T} \qquad (3)$$

Where $m = (I/A)$ is an order parameter, H is its conjugate variable and a-c are fitting parameters. If we force the parameter c to be 0 in eq. 3, i.e. we reduce the Landau free energy to fourth order. Fitting the data of Fig. 1 we obtain $a = 19.2$ and $b = -130.73$. This result is unphysical since it implies that the free energy is negative for large m. A fit using eq.3 gives the following values for the ^{64}Ni + ^{58}Ni (^{64}Ni + ^{232}Th): a = 23.5(18.86), b = -413.8(-260.3), c = 2848.3(1408.1) and H/T = 0.79(1.06) and is displayed in Fig. 1(long dashed line). This case corresponds to a 'classical' second-order phase transition.

For first-order phase transitions, the following relation between parameters should hold,

$$b = -4\sqrt{ca/3} \qquad (4)$$

Using the values of a and c given above we get b=-597.5 (-376.3) which is close to the fitted values given above. In particular if we substitute eq.(4) into eq.(3) and perform the fit, we obtain a result shown by the short-dashed line. In the case of the first-order transition the fit bends up for large (positive) m, however the data do not distinguish between the two cases. Further study and discussion on the relation between the isotope distribution and the order parameter are now underway.

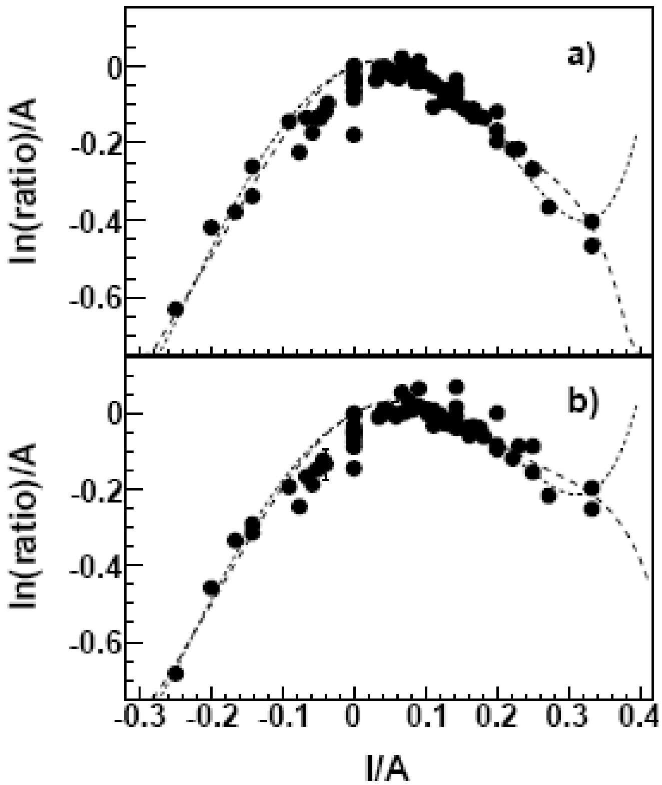

Figure 1. The negative of the free energy versus symmetry term for the case ^{64}Ni+^{58}Ni (upper panel) and ^{64}Ni+^{232}Th at 40 MeV/nucleon (lower panel). The dashed lines are fits based on Landau O(m6) free energy either for a second-order(long-dashed) or first-order (short-dashed) phase transition (see text).

[1] A. Bonasera *et al.*, Rivista Nuovo Cimento **23**, 1 (2000).

[2] K. Huang, *Statistical Mechanics*, *2nd edition* (J. Wiley and Sons, New York, 1987), Ch.16-17; A. Hosaka and H. Toki, *Quarks, Baryons and Chiral Symmetry* (World Scientific, Singapore, 2001).

[3] L. D. Landau and E. M. Lifshitz, *Statistical Physics*, *3rd edition* (Pergamon press, New York, 1989).