BRIEF REPORTS

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Isotope yield ratios of fragments from heavy-ion reactions

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Isotope yield ratios produced in collisions of 35 MeV/nucleon ^{14}N with targets of C, Ni, Ag, and Ho have an exponential dependence on total neutron-to-proton ratio. A statistical multifragmentation model including particle emission from excited fragments predicted such behavior for yield ratios measured earlier at the higher energy of 84 MeV/nucleon.

When an excited nucleus emits fragments, it is to be expected that the yield ratio of two isotopes of an element will depend on the N/Z, neutron-to-proton, ratio of the emitting system. When the emitting system was assumed to be the combined system of target and projectile, it was found[1,2] that the isotope ratio had a systematic dependence on N/Z, an exponential dependence. Specifically, this dependence was found in heavy-ion collisions of ^{12}C and ^{18}O at 84 MeV/nucleon for the three yield ratios ^{7}Li/^{6}Li, ^{11}B/^{10}B, and $^{9-11}$Be/^{7}Be. The authors demonstrated that, with a quantum statistical interpretation, the ratios were consistent with an entropy per nucleon of ~ 2.2 and with breakup temperature ~ 5 MeV and relative density $\rho/\rho_0 < 0.2$.

Barz *et al.*[3] were able to obtain the exponential behavior with a statistical multifragmentation model. They took account of the fact that many of the original fragments are in particle-unstable excited states. Evaporation from these fragments then narrows the isotope range of the experimentally observed fragments. They showed that the linear dependence of neutron chemical potential on N/Z, $\mu_N = \mu_{N_0} + \mu'_N(N/Z)$, can most easily be obtained by invoking a grand canonical approach,[4-6] which then gives for the isotope yield ratio the approximate dependence on N/Z

$$R \sim \exp[-(\Delta N)\mu_N/T] \sim \exp[-(\Delta N)\mu'_N(N/Z)/T] , \quad (1)$$

where T is the source temperature and ΔN is the difference in the number of neutrons of the two isotopes. For the three measured ratios[1,2] listed above (^{7}Li/^{6}Li, ^{11}B/^{10}B, and $^{9-11}$Be/^{7}Be) $\Delta N = 1$, 1, and 2–4, respectively. The data are in qualitative agreement with the predicted greater slope of R vs N/Z for the Be isotopes.

In two experiments with a ^{14}N beam at 35 MeV/nucleon from the K500 cyclotron at Michigan State University, yields were measured for two isotopes of lithium and three isotopes each of beryllium, boron, and carbon. Hence we could deduce ten yield ratios, six for which $\Delta N = 1$, three with $\Delta N = 2$, and one having $\Delta N = 3$. The targets were C, Ni, and Ho in one experiment[7] and Ag in the other.[8] In all cases the quasielastic component was separated out, and only the deep-inelastic part was used for determining yield ratios. In the C, Ni, and Ho experiment the angular range of observation was only 7°–23°, not enough to determine the total, angle-integrated yields. In the Ag experiment, however, the range was 15°–83°, which was enough to do a moving-source fit to isotope spectra at seven angles, and from the fit to obtain the total yield. This was done for each of the ten isotopes. Hence, for the Ag target we could obtain all the isotope yield ratios. We could also integrate from 7° to 23° and obtain yield ratios over this limited angular range. Fortunately, in every case, the limited-yield ratio was within 20% of the total-yield ratio. Making the assumption that these approximate equalities were also valid for targets of C, Ni, and Ho, we could obtain yield ratios for all the targets.

As in Refs. 1 and 2, the yield ratios for each element are plotted in Fig. 1 against N/Z, where N and Z are the neutron and proton numbers for the combined system, projectile plus target. The left part of the figure has the $\Delta N = 1$ cases, the upper right part the $\Delta N = 2$ cases, and

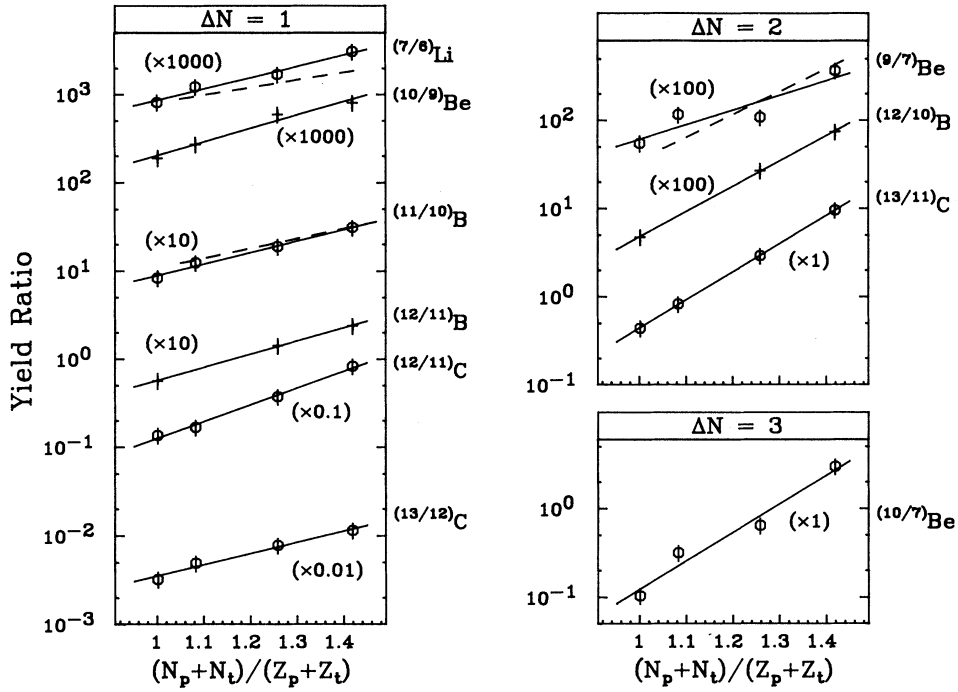

FIG. 1. Isotope yield ratios vs neutron-to-proton ratio of the combined system, projectile (p) plus target (t). The points are the data, the solid straight lines are fits to them, and the dashed lines are fits to the data of Ref. 1. ΔN, the difference in the number of neutrons in the two isotopes of a ratio, is one for the six ratios at the left, two for the three ratios at the upper right, and three for the one ratio at the lower right. For clarity, the data and fits have been multiplied by various factors before plotting; the factors are given in parentheses. The scales are the same in the three parts of the figure.

the lower right the one case for $\Delta N = 3$. The solid lines, which are straight-line fits to the data, illustrate the exponential dependence of yield ratio on N/Z—the same type of dependence found by Wada *et al.*[1,2] Indeed, the slopes, and even the absolute values, of the lines fitting the data of Wada *et al.* are similar to ours. Their fits are represented by the three dashed lines in Fig. 1. (The dashed line in the upper right part of the figure, copied from Ref. 1, is for the collection of isotopes $^{9-11}$Be rather than for the single isotope ^{9}Be.) The increasing steepness of the lines with increasing ΔN is in overall, but not in quantitative, agreement with Eq. (1).

There are two points to be noted about the data of Fig. 1. First, the Li ratios are upper limits because our detectors did not distinguish between ^{7}Li fragments and the two alpha particles from ^{8}Be decay. Although the fraction of ^{8}Be decay captured by our detectors is a calculable function of ^{8}Be kinetic energy and detector solid angle, the actual yield of ^{8}Be is not known. The other point is that with the yields of three isotopes, as we have for each of three elements, one can compute three yield ratios. Although only two of them are independent, we have shown all three in Fig. 1.

It is clear that Eq. (1) fits our data about as well as they fitted the somewhat more limited data set of Wada *et al.* Perhaps this is surprising since the latter experiment was done at 84 MeV/nucleon and ours at only 35 MeV/nucleon. If the higher-energy data are to be understood in terms of a statistical multifragmentation model, is the model also valid at the much lower energy of 35 MeV/nucleon?

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