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MICROSCOPIC AND MACROSCOPIC MODEL CALCULATIONS
OF RELATIVISTIC HEAVY ION FRAGMENTATION REACTIONS

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Abstract

The possibility of observing neutron-proton correlations in the nuclear ground state via relativistic heavy-ion reactions is examined. The isotope production cross sections from the reaction of 213 MeV/nucleon ^{40}Ar with ^{12}C are calculated with a correlated abrasion-ablation model and with an uncorrelated intranuclear cascade model, and the results compared to recent experimental data. The neutron-proton correlations may only be visible in products near the mass of the fragmenting nucleus.

The reaction of 800 MeV protons with uranium has been used previously to produce neutron rich isotopes of the light elements.¹ The use of relativistic heavy ion (RHI) reactions to produce unknown neutron excessive nuclei has been recently suggested by Bondorf et al.,² and carried out by Symons et al.³ The suggestion stemmed from the possibility of removing neutrons and protons from a given target (or projectile) nucleus in proportion to their number in that nucleus by a RHI reaction and then observing the residue of the target (or projectile) nucleus which would now be, in general, neutron excessive. However, before the residue can be observed in the laboratory it will have undergone a deexcitation process to remove any excitation energy deposited in the primary fragment by the interaction. This deexcitation process will remove (again, in general) more neutrons than protons from the primary fragment and make the production of very neutron excessive residues difficult. Thus, the production of very neutron excessive residues will rely on the variance of the neutron to proton ratio of the removed nucleons, and the excitation energy of the primary fragment. The fundamental question of the correlation of nucleons in the ground state will specify the neutron to proton ratio variance. In this letter we explore the visibility of ground state nuclear correlations in projectile fragmentation in the reaction of 213 MeV/nucleon ^{40}Ar with ^{12}C . For these calculations we have used two parameter free

models; a macroscopic model including neutron-proton correlations and a microscopic model without such correlations. The results of these two calculations are compared to the measured data of reference 3 and the observation of correlations in the nuclear ground state is discussed in the light of the comparisons.

The macroscopic model of RHI reactions that we have used is the abrasion-ablation model⁴⁻⁶ with the neutron-proton correlations introduced by Morrissey et al.⁷ In this view of RHI reactions the target and projectile are taken to be hard spheres which move on straight line trajectories. Those nucleons that lie in the region of overlap of the two nuclei are removed in the abrasion stage of the interaction. The spectator fragments of the target (and projectile) are then assigned an excitation energy proportional to their distortion,⁴ without the excess excitation energy of the FSI process of Rasmussen et al.⁶ The assumptions used to justify the FSI process are not valid for the lower energies used in these calculations. The primary products are then allowed to deexcite through a statistical evaporation chain.^{6,7} The variance in the neutron to proton ratio of the nucleons removed in the fast state of the reaction (i.e., the neutron-proton correlation) is calculated from the zero point quantum vibrations of the giant dipole resonance.⁷ This calculation can be viewed as a leading term approximation to the correlated model of Bondorf et al.² in which higher order vibrations are included.

The calculated primary fragment distribution for ^{40}Ar fragmentation can be seen in Fig. (1a) and the distribution of projectile residues after their deexcitation can be seen in Fig. (1b). We have arbitrarily cut off the calculations at $Z \approx 8$ for two reasons: (1) for the most central collisions the abrasion model unrealistically generates primary fragments which have a cylindrical hole through their center, and (2) statistical deexcitation of nuclei with such low mass numbers is probably not justified.

The microscopic model of RHI reactions that we have used in these calculations is that of an intranuclear Monte Carlo cascade.⁸ This calculation was made using an extension of the intranuclear cascade code,⁹ VEGAS, for proton induced reactions which has been modified to treat two colliding nuclei.⁸ The calculations were performed with step-function density distributions for both nuclei and without refraction and reflection at the nuclear boundaries for the cascading particles. Meson production and cascades are included via the Isobar model.¹⁰ Fermi motion was included in the projectile as well as the target. The impact parameters for the collisions were selected at random, and the cross sections were integrated over impact parameter. The results for the primary fragment production cross sections, before the statistical deexcitation process, are shown in Fig. (1c). These fragments are then individually deexcited using a version of the Dostrovsky, Fraenkel and Friedlander statistical model Monte Carlo calculations.^{11,8}

The final residue distribution from these calculations is shown in Fig. (1d). These calculations were also cut off at $Z \sim 8$ for the second reason mentioned above, that is, that statistical deexcitation of these nuclei is probably not justified.

Comparison of the primary fragment cross section distributions from the two models, Figs. (1a) and (1c), show that these distributions are very dissimilar. The difference in the correlations among the removed nucleons between the two calculations can be seen in the width of the Z distributions at constant mass number. The uncorrelated distribution is approximately twice as wide as the correlated one. A second difference that is easily noted is the failure of the cascade calculation to remove as many nucleons in the fast stage as the abrasion model. However, the final residue cross section distributions are quite similar, as shown in Figs. (1b) and (1d). This comes about because of the relatively large amounts of excitation energy deposited in the primary fragments in the case of the cascade calculation, indicated in Fig. 2, as compared to the small amount in the primary interaction in the abrasion calculation. The excitation energies of the abrasion fragments with numbers of removed nucleons comparable to those in Fig. 2 range from ~ 0 MeV to ~ 20 MeV.

The similarity of the two calculations is emphasized in Fig. 3 where the data for the absolute cross sections for the production of oxygen, fluorine and neon isotopes from reference 3 is compared to our calculations. As indicated in Figs. (1b)

and (1d) the two calculations give very similar results, which are in reasonable agreement with the measured data for the production of these elements. The main features of the calculated isotopic distributions for those elements not adjacent to the projectile nucleus, and the reported data, are that they peak at or near the bottom of the valley of beta stability and have nearly constant widths. Therefore, because the final products result from highly excited primary products, in both models, the large differences observed in the primary product distributions do not survive the strong focusing effect of the statistical deexcitation process into the valley of beta stability. As a result, the final isotope distributions bear the characteristics of the valley of beta stability and pre-equilibrium features of the distributions (such as those due to ground state correlations) are washed out by the statistical process.

These calculations indicate that the effect of ground state correlations on the residue production cross sections should be most prominent for those nuclei produced with low excitation energies. Both models predict the lowest initial excitation energies for those nuclei nearest the mass and charge of the target (and projectile) nucleus. This can be seen in Figs. (1b) and (1d) where the greatest difference between the two calculations is observed for products with $Z = 18$ and 17 . Unfortunately, the data reported in reference 3 did not extend into this critical region.

We can summarize our results as follows: the measured

isotope production cross sections for the fragmentation of ^{40}Ar on a ^{12}C target are in general agreement with the absolute predictions of the uncorrelated intranuclear cascade model and the correlated abrasion-ablation model. This may be due, in part, to the lack of measurements of near-projectile residues, where the two models are most different. Because of the high excitation energies deposited in the primary fragments by the interaction, and the nature of statistical processes, the effects of correlations in the nuclear ground state (or, lack thereof) will only be visible in residues that result from peripheral collisions where the excitation energy is predicted to be minimized. Future experiments using projectiles with higher N/Z ratios, as suggested in reference 3, will be helpful in exploring the difference between these models and the effects of ground state correlations if the measurements can be extended to those products where the total interaction has removed only a few nucleons from the projectile.

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Figure Captions

Fig. 1. The primary fragment isotope production cross sections calculated with the macroscopic, abrasion-ablation, model and the microscopic, Monte Carlo, model are shown in panels (a) and (c), respectively. The final residue isotope production cross sections obtained after the statistical deexcitation of (a) and (c) are shown in panels (b) and (d), respectively.

Fig. 2. The primary fragment excitation energies obtained in the Monte Carlo calculations are shown as a function of mass removed by the fast cascade. The excitation energies have been sorted into 50 MeV wide bins to emphasize the high excitation energies obtained in this model.

Fig. 3. A comparison of the calculated residue isotope production cross sections with the measured data of reference 3. The solid curve is from the macroscopic model, the histograms are from the microscopic model, and the data³ are shown by the solid points.

Figure 1

XBL 792-585

Figure 2

Figure 3

XBL 792-591

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