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LARGE COLLISION RESIDUES AND NUCLEAR FISSION IN RELATIVISTIC HEAVY ION REACTIONS*

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ABSTRACT

Target residue mass and charge distributions have been measured radiochemically for 76 products of the interaction of 25.2 GeV ^{12}C with U. The mass yield curve shows two prominent bumps; one for $80 \leqslant A \leqslant 145$ resulting from the modest excitation energy [50-100 MeV] fission of a species with $A \sim 225$, and the second for $160 \leqslant A \leqslant 190$ apparently due to the survivors of a more central collision between projectile and target.

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There has been a great deal of interest in recent years in studies of relativistic heavy ion (RHI) reactions, prompted in part by the possibility of studying nuclear matter at high densities, studying nuclear shock waves, etc.[1] Experimental measurements by Schroeder et al.[2] and Westfall et al.[3] have shown that in RHI reactions with heavy targets, some encounters lead to large numbers of emitted charged particles (up to 100) and that these emitted particles show very "hard" energy spectra, uncharacteristic of evaporated nucleons. Several theoretical attempts have been made to explain these light particle multiplicities and energy spectra, with the most notable success being the simple geometric-thermodynamic "fireball" model of Westfall et al.[3] According to this model, in the initial encounter between the projectile and target, a group of nucleons is cut out from the overlapping regions of the target and projectile. This group of nucleons forms a hot quasiequilibrated fireball which decays as if it was an ideal gas.

In this paper, we report the results of radiochemical measurements of the yields of the target residues formed when 25.2 GeV ^{12}C ions interact with a natural U target. The purpose of this investigation was to see if the target residue mass and charge distributions show any unusual features that could help us to understand the mechanism of these RHI reactions with heavy targets. Other radiochemical studies of RHI reactions with lighter targets by Rudy and Porile[4] (Ag + C), and by Cumming et al.[5,6] (Cu + C,N) indicated little difference (except in the light product yields) between the RHI reactions and reactions induced by GeV protons, although track detector studies by Katcoff and Hudis[7] (U + N) did show enhanced fission cross sections in the RHI reactions.

The target array for this experiment consisted of 3 foils of natural uranium separated from each other by ~150 mm.

The foils, varying in thickness from 33 to 72 mg/cm^2 and surrounded by ~15 mg/cm^2 Al catcher foils, were irradiated for 162 minutes in a beam of 25.2 GeV ^{12}C ions of intensity ~2.5 × 10^{10} particles/min at the BEVALAC. Gamma and x-ray spectroscopic measurements of the radioactivity induced in the target and catcher foils began one hour after bombardment and continued for about three weeks. Over 75 radionuclides were identified on the basis of their γ-ray energy, half-life and relative γ-ray abundance. Based upon the variation of activity with foil thickness, corrections (of ~10-30%) were made to each measured activity to account for the effects of secondary-induced reactions. The corrections were roughly independent of A with maximum corrections being applied to the neutron-rich fission product activities. Recoil losses from the target were measured to be negligibly small.

The experimentally determined independent and cumulative yields for individual radionuclides are shown in Figure 1(a). Using the procedures described by Otto et al.[8], independent yield formation cross sections were calculated for all radionuclides, Gaussian charge dispersions [of the form $P(Z,A) = (2\pi\sigma^2)^{-1/2}\exp(-(Z-Zp)^2/2\sigma^2)$] were fitted to these data, and the charge dispersions were integrated to give the yield of each A in the reactions. Figure 1(b) depicts the data of Figure 1(a) plotted to show the (Z,A) distribution of the products while Figure 1(c) shows the mass yield distribution for the reaction. The estimated isobaric yields shown in Figure 1(c) exceed the highest measured independent and cumulative yields for a given mass region by a factor of 2-3 (due to the integration of the assumed Gaussian charge dispersion over several isobars) except for the region $165 \leqslant A \leqslant 183$ where the ratio of estimated isobaric yield to highest measured cumulative yield is ~4. This is due to the fact that Zp, the most probable fragment charge, for this region lies on the line of β-stability and greater corrections must be made for unmeasured yields. Nevertheless, the dramatic bump in the mass yield curve in the region from $160 \leqslant A \leqslant 190$ is also seen in the measured nuclide yields shown in Figure 1(a), thus indicating it is not an artifact of the data reduction procedures.

Based upon the shapes of the mass and charge distributions, product nuclei with $70 \leqslant A \leqslant 140$ are assumed to result from binary fission of a target-like residue. As seen in Figure 1(c) the mass distribution for the 25.2 GeV ^{12}C ion induced fission of U is similar in shape to the distribution for the 28 GeV p induced fission of U.[9] As pointed out by Katcoff and Hudis[7], the higher absolute cross sections observed in the RHI reactions are due mostly to the increased total reaction cross section for RHI's. The fission product charge dispersions are characterized by width parameters $\sigma \sim 0.9-1.2$ Z units. Direct comparision of these width parameters with those from a number of other high energy fissioning systems of known excitation energy allows one to infer the average excitation energy for the fissioning system(s) to be 50-100 MeV. The fission product charge dispersions observed in this work are very different from those observed in GeV proton induced fission of U. Our charge dispersion curves for the region of $110 \leqslant A \leqslant 140$ are single Gaussians with $\sigma \sim 0.9$ while the dispersions observed for 11 GeV proton induced fission of U[10] are interpreted as the sum of two Gaussians with widths $\sigma = 1.0$ and 1.8 for the neutron excessive and deficient components, respectively. The Zp for our data occurs approximately halfway between the n-excessive component and n-deficient component Zp values of Yu and Porile.[10]

The most interesting new feature observed by us is the surprising large bump in the mass yield curve in the region from $160 \leqslant A \leqslant 190$, a feature totally absent from the GeV p reaction mass yield curve. The preferential population of the low spin member of the isomeric pair ^{186m,g}Ir ($\sigma(^{186m}\mathrm{Ir}(2-))/\sigma(^{186}\mathrm{Ir}(6-)) \approx 12 \pm 4$) implying low final product angular momentum is another intriguing feature of yields in this region. We have done a set of simple calculations to see what we can infer about the reaction mechanism(s) responsible for this bump. We have assumed that any mechanism for the initial projectile-target encounter and pre-equilibrium non-fission fast dissipation of excitation energy must eventually lead to a point at which statistical equilibrium is achieved and further de-excitation of the resultant species can be traced with a standard statistical de-excitation calculation. We have done such statistical de-excitation calculations using a modified version of the ALICE code,[11] which allows for fission-neutron-charged particle emission competition with $J_{rms} \lesssim 10\hbar$ (as suggested by our isomer ratio data). By assuming various sets of initial product yields and excitation energies and tracing their de-excitation, we were able to determine what set of initial conditions lead to the observed product yields. Assuming the data are properly represented by the curve C in Figure 1(c), the product yields and excitation energies at the time at which fission begins to compete with particle emission (i.e., the start of the statistical de-excitation process) are shown by curve A. Curve A is consistent with the fission component of the mass distribution in that the sum of the yields of all species that fission in the de-excitation process is approximately equal to one-half the sum of the yields with A=80-140, although the detailed shape of curve A for A>210 is not uniquely specified by the data. Upper limits on the excitation energy of species on curve A with A<200 and lower limits on species with A>200 are primarily set by fission competition with $J \leqslant 10\hbar$. An upper limit on the product angular momentum at the time at which fission begins to occur is presumably set by the rotating liquid drop limit[11] on fission barriers for A=180 species of ~$90\hbar$.

It is interesting to speculate as to what processes gave rise to the distribution represented by curve A.

Curve B in Figure 1(c) shows the predictions for product yields and excitation energies as given by a calculation employing the geometrical concepts of the fireball model,[3] assuming the incident ^{12}C ion makes a "clean cut" through the nucleus, weighting each impact parameter by the geometrical cross section associated with it, assuming the excitation energy of each species formed is simply the increase in nuclear surface energy due to the cut, and <u>not</u> allowing for any subsequent pre-equilibrium emission of neutrons and protons. Clearly a more refined version of this model is needed to fit the data. On the other hand, reasoning from the fact that the fission cross section is ~1/2 the total reaction cross section[7] and the mean fissioning system mass is greater than the mean mass of the "large residue nuclei," we are led to conclude that the impact parameter $b \lesssim 0.7\ (R_t + R_p)$ for events leading to the "large residue nuclei." In any case it will be interesting to see how sophisticated theories of RHI interactions quantitatively account for our curve A.

In summary, we can say that we find the RHI-induced fission of U appears to be a modest excitation energy (50-100 MeV) process with (a) a single humped charge dispersion (b) involving nuclei with A~225 and (c) resulting from impact parameters $b \gtrsim 0.7\ (R_t + R_p)$. The non-fissioning survivors of collisions with $b \lesssim 0.7\ (R_t + R_p)$ appear to form a bump in the mass-yield curve for $160 \leqslant A \leqslant 190$. Statistical de-excitation calculations allow us to deduce the yields and excitation energies of the precursors of these "large residue nuclei" that result from the primary (initial interaction-fast preequilibrium de-excitation) step of the reaction.

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FOOTNOTES AND REFERENCES

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FIGURE CAPTION

Fig. 1. (a) Independent and cumulative yield formation cross sections for individual radionuclides. (b) Contour lines for equal independent yields. The two main bumps observed are due to the fission product and central collision survivor distributions. Subsidiary features include enhanced yields of products with N=82 and low Z products. (c) Total integrated mass yields. Dotted curve is from ref. 9. See text for explanation of other curves. The numbers in parentheses along curves A and B refer to the excitation energies in MeV of species of given mass.

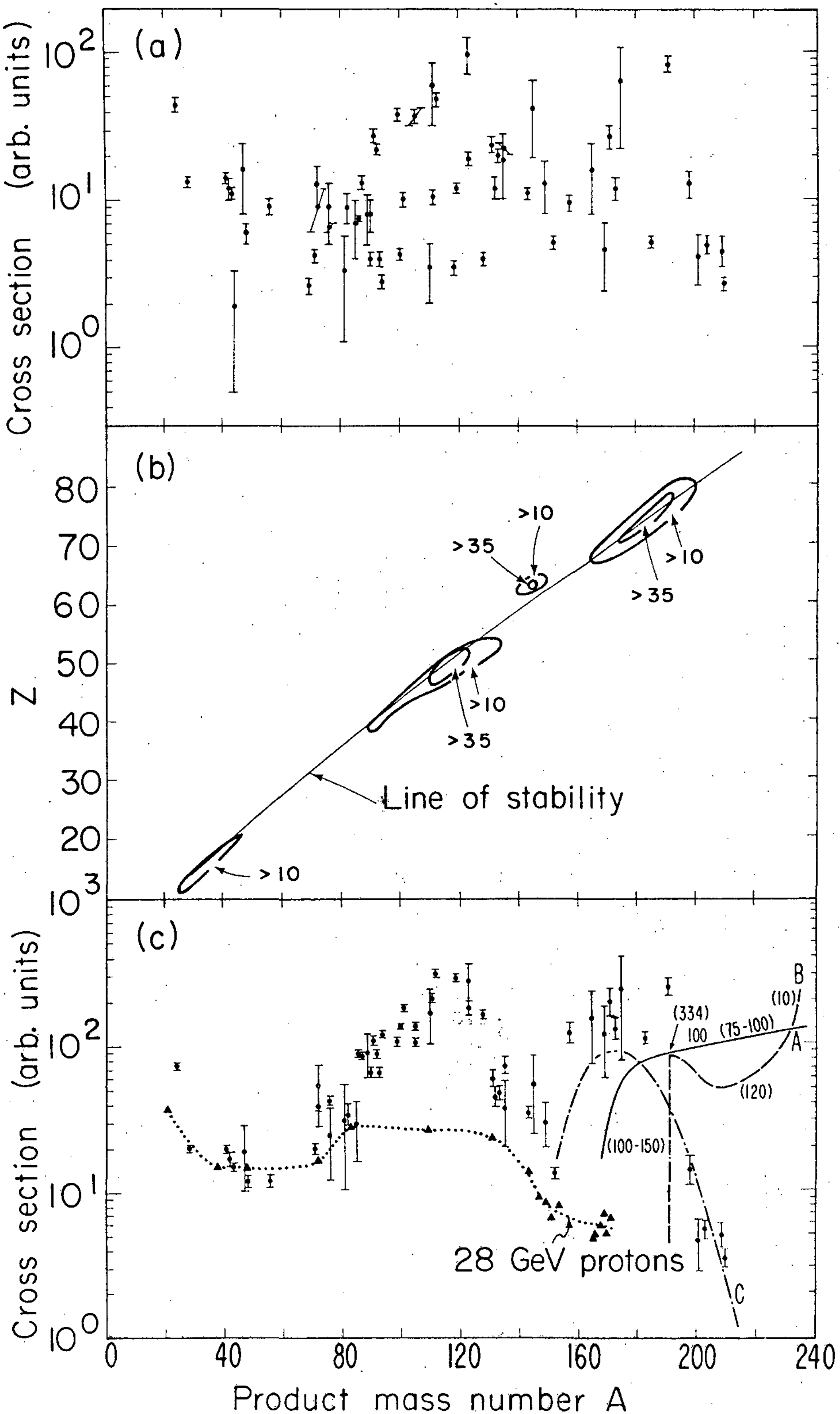

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Fig. 1

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