Large Collision Residues and Nuclear Fission in the Interaction of 25.2-GeV ^{12}C with Uranium

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

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[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 were an ideal gas.

In this Letter, we report the results of radioanalytical 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 radioanalytical studies of RHI reactions with lighter targets by Rudy and Porile[4] (Ag + C) and by Cumming and co-workers[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 three 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 $\sim 2.5 \times 10^{10}$ particles/min at the Bevalac. γ- and x-ray spectroscopic measurements of the radioactivity induced in the target and catcher foils began 1 h 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 Fig. 1(a). Using the procedures previously described in detail,[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 Fig. 1(a) plotted to show the (Z, A) distribution of the products while Fig. 1(c) shows the mass yield distribution for the reaction. The estimated isobaric yields shown in Fig. 1(c) exceed the highest measured independent and cumulative yields for a given mass region by a factor of 2–3 (because of the integration of the assumed Gaussian charge dispersion over several isobars) except for the region $165 \leq A \leq 183$ where the ratio of estimated isobaric yield to highest measured cumulative yield is ~4. This is because Zp, the most probable fragment charge, for this region lies on the line of β stability and greater corrections

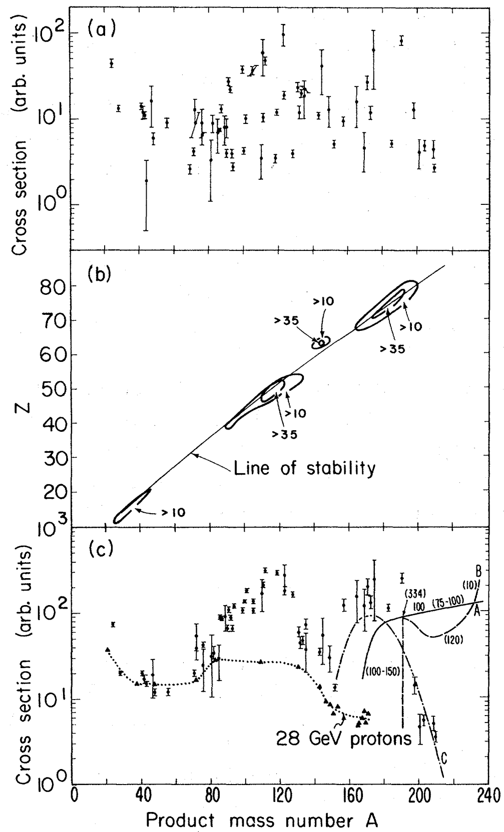

FIG. 1. (a) Independent and cumulative yield formation cross sections for individual radionuclides. (b) (b) Contour lines for equal independent yields. The two main bumps observed are due to the fission-product and central-collision-survivor distributions. Subsidiary features include enhanced yields 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.

must be made for unmeasured yields. Nevertheless, the dramatic bump in the mass curve in the region from $160 \leq A \leq 190$ is also seen in the measured nuclide yields shown in Fig. 1(a), thus indicating that it is not an artifact of the data reduction procedures.

Based upon the shapes of the mass and charge distributions, product nuclei with $70 \leq A \leq 140$ are assumed to result from binary fission of a target-like residue. As seen in Fig. 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 $\sigma \sim 0.9-1.2$ of units Z. Direct comparison of these width parameters with those from a number of other high-energy fissioning systems of known excitation energy[10] 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 $110 \leq A \leq 140$ are single Gaussians with $\sigma \sim 0.9$ while the dispersions observed[11] for 11-GeV proton-induced fission of U 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.[11]

The most interesting new feature observed by us is the surprising large bump in the mass yield curve in the region from $160 \leq A \leq 190$, a feature totally absent from the GeV p-reaction mass-yield curve. The preferential population of the low-spin member of the isomeric pair $^{186m,g}Ir$ $[\sigma(^{186m}Ir(2^-))/\sigma(^{186}Ir(6^-)) \approx 12 \pm 4]$, 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 nonfission fast dissipation of excitation energy must eventually lead to a point at which statistical equilibrium is achieved and that 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,[12] which allows for fission-neutron charged-particle emission competition with $J_{\mathrm{rms}} \leq 10\hbar$ (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 leads to the observed product yields. On the assumption that the data are properly represented by the curve C in Fig. 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. It is this "conservative" feature of curve A that causes us to normalize vertically curve C to a slightly lower position (although within the experimental uncertainties) than the observed mass yields. 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 $J \leq 10\hbar$. 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[12] on fission barriers for $A = 180$ species of $\sim 90\hbar$.

It is interesting to *speculate* as to what processes gave rise to the distribution represented by curve A. Curve B in Fig. 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 that 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 that the excitation energy of each species formed is simply the increase in nuclear surface energy due to the cut, and *not* 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 $\sim \frac{1}{2}$ 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 (a) with a single-humped charge dispersion, (b) involving nuclei with $A \sim 225$, and (c) resulting from impact parameters $b \gtrsim 0.7(R_t + R_p)$. The nonfissioning survivors of collisions with $b \lesssim 0.7(R_t + R_p)$ appear to form a bump in the mass-yield curve for $160 \leq A \leq 190$. 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 pre-equilibrium de-excitation) step of the reaction.

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[1]G. F. Chapline, M. H. Johnson, E. Teller, and M. S. Weiss, Phys. Rev. D 8, 4302 (1973).

[2]L. S. Schroeder, Lawrence Berkeley Laboratory Report No. LBL-5082, 1976 (unpublished).

[3]G. D. Westfall *et al.*, Phys. Rev. Lett. 37, 1202 (1976).

[4]C. R. Rudy and N. T. Porile, Phys. Lett. 59B, 240 (1975).

[5]J. B. Cumming, R. W. Stoenner, and P. E. Haustein, Phys. Rev. C 14, 1554 (1976).

[6]J. B. Cumming *et al.*, Phys. Rev. C 10, 739 (1974).

[7]S. Katcoff and J. Hudis, Phys. Rev. C 14, 628 (1976).

[8]J. V. Kratz, J. O. Liljenzin, A. E. Norris, and G. T. Seaborg, Phys. Rev. C 13, 2347 (1976); I. Binder, Ph.D. thesis, University of California, Berkeley, Lawrence Berkeley Laboratory Report No. LBL-6526, 1977 (unpublished); W. Loveland, D. J. Morrissey, R. J. Otto, and G. T. Seaborg, Lawrence Berkeley Laboratory Report No. LBL-6527, 1977 (unpublished).

[9]Y. Y. Chu, E. M. Franz, G. Friedlander, and P. J. Karol, Phys. Rev. C 4, 2202 (1971).

[10]See, for example, R. L. Folger, P. C. Stevenson, and G. T. Seaborg, Phys. Rev. 98, 107 (1955); J. A. McHugh and M. C. Michel, Phys. Rev. 172, 1160 (1968); A. C. Wahl, in *Proceedings of the Symposium on the Physics and Chemistry of Fission, Salzburg, Austria, 1965* (International Atomic Energy Agency, Vienna, Austria, 1965).

[11]See, for example. Y. W. Yu and N. T. Porile, Phys. Rev. C 7, 1597 (1973).

[12]F. Plasil and M. Blann, Phys. Rev. C 11, 508 (1975).