Energy dependence of ^{209}Bi fragmentation in relativistic nuclear collisions

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The results of cross-section measurements for the reactions ^{209}Bi(^{12}C,X)Au, $E = 4.8$ and 25.2 GeV and ^{209}Bi(^{20}Ne,X)Au, $E = 8.0$ GeV are reported. The observed yields of the gold isotopes show a similar dependence on mass number for each reaction, differing slightly in the position of the centroid of the distribution. As the projectile energy increases, the inferred excitation energy of the primary residues remains the same or decreases slightly. This observation is in agreement with the predictions of the intranuclear cascade model of relativistic heavy ion collisions.

[NUCLEAR REACTIONS ^{209}Bi(^{12}C,X)Au, E=4.8, 25.2 GeV; ^{209}Bi(^{20}Ne,X)Au, E= 8.0 GeV; measured Au isotopic distributions, relativistic heavy ions, target fragmentation, Ge(Li) spectroscopy.]

An ambiguous point in the description of relativistic heavy ion (RHI) reactions is the amount of excitation energy deposited in the spectator fragments during the interaction. Various models of the fast interaction generate primary fragments with differing amounts of excitation which after de-excitation reproduce the experimental results for light nuclei.[1,2] Although direct measurements of this excitation energy are difficult, one can follow the trend of primary fragment excitation by performing some relatively simple experiments. Excitation energy in a high mass (but relatively nonfissionable) nucleus at low angular momentum is removed mostly by evaporated neutrons. Thus, if the primary fragment cross section distributions are governed by geometry, then the differences in the N/Z ratio of the final residues of RHI reactions as a function of bombarding energy (same projectile and high mass target) will represent differences in the excitation energy.

Following this idea, in this communication we report the variation of the production of gold isotopes from three RHI reactions with ^{209}Bi. In these experiments bismuth metal foils surrounded with Mylar catchers were irradiated with beams of 4.8 GeV (0.40 GeV/nucleon) ^{12}C, 8.0 GeV (0.40 GeV/nucleon) ^{20}Ne, and 25.2 GeV (2.1 GeV/nucleon) ^{12}C ions from the LBL Bevalac facility. The details of the irradiations are given in Table I. The target fragmentation products stopped in the target or catcher foils and the induced radioactivities were measured by gamma ray spectroscopy of the target foils and chemically separated gold fractions.[3] These measurements were made on the sample at regular intervals over a period of from 30 min to one year after irradiation. The gamma ray emitting nuclei were identified using standard techniques[4] and the production cross sections were calculated for those activities observed in the unseparated foils. The activities observed in the chemical samples were normalized to those seen in the unseparated foils. However, this normalization was not possible for the 25.2 GeV ^{12}C data because only one foil was irradiated and chemically processed, and therefore these production cross sections are expressed in arbitrary units. The contribution of secondary induced reactions to the Au product yields was studied by comparison of the activities of the two unseparated foils from the 4.8 GeV ^{12}C + ^{209}Bi bombardment which differed by a factor of ~2 in thickness. This comparison showed that ~30% of the ^{198}Au^{g} yield in the thickest target (~0.25% mg/cm^2) was due to such effects, while the lighter nuclidic activities had little or no secondary contributions. This secondary reaction correction was applied to the $A \geq 198$ product yields for the two reactions with ~135 mg/cm^2 targets, while all other secondary reaction contributions were assumed to be negligible.

The measured cumulative yield cross sections (which include contributions from nuclei produced by radioactive decay) were corrected for this decay feeding by an iterative fitting of Gaussian distributions to the decay-corrected (and independent yield) cross sections.[4] The resulting calculated and measured independent yield cross sections $\sigma(Z,A)$ are shown in Fig. 1 and included in Table I. The uncertainties given for $\sigma(Z,A)$ reflect the contribution from statistical uncertainties from the measurements and an *ad hoc* factor of 20% of the β-decay feeding correction where applied.[5] The yield of ^{194}Au is depressed relative to the other nuclidic yields in all the reactions for reasons that are not clear.

The number of Au isotopes that were observed in each reaction was limited by two factors; the low activity levels of the neutron rich species and the short half-lives (relative to the chemical separation time and length of the bombardment)

TABLE I. Experimental conditions and results.

Projectile energy (GeV)	^{12}C 4.8		^{20}Ne 8.0		^{12}C 25.2	
Target thickness (mg/cm^2)						
(1) unseparated	112.6, 227.7		116			
(2) chemical	132.9		137		~50	
Bombardment statistics [total particles (hours)]						
(1) unseparated	6.19×10^{13} (13.7)		3.64×10^{13} (13.5)			
(2) chemical	6.19×10^{13} (13.7)		3.75×10^{13} (13.5)		5.3×10^{12} (2.7)	
Cross sections						
	σ_{OBS} (mb)	σ_{IY} (mb)	σ_{OBS} (mb)	σ_{IY} (mb)	σ_{OBS} (a.u.)	σ_{IY} (a.u.)
^{190}Au	12.9 ±1.3	8.2 ±1.4	23.0 ±2.3	13.6 ±2.5		
^{191}Au	12.9 ±1.3	8.1 ±1.4	17.7 ±1.7	10.4 ±1.9	28.4±2.8	14.2±1.4
^{192}Au	11.9 ±1.2	7.7 ±1.3	16.9 ±1.7	9.4 ±1.9	25.6±2.6	15.5±1.5
^{193}Au	11.6 ±1.2	7.7 ±1.3	13.5 ±1.4	8.2 ±1.6	20.7±2.1	14.6±1.5
^{194}Au	1.7 ±0.2	1.7 ±0.2	1.8 ±0.2	1.8 ±0.2	4.6±0.5	4.6±0.5
^{195}Au	11.5 ±1.1	3.4 ±0.3	13.1 ±1.3	3.7 ±0.4		
^{196}Au^{m+g}	1.2 ±0.1	1.21±0.1	1.24±0.094	1.24±0.014	4.2±0.5	4.2±0.5
^{198}Au^{m+g}	0.65±0.052	0.65±0.052	0.51±0.039	0.51±0.039	2.3±0.2	2.3±0.2
^{199}Au	0.56±0.056	0.54±0.058	0.24±0.026	0.24±0.026	1.4±0.1	1.4±0.1
Isotopic distribution centroids $\langle A\rangle$ for $Z=79$						
Experimental	191.4±0.3		191.6±0.5		192.1±0.3	
Cascade model (Ref. 8)	189.4±0.3		189.5±0.5		190.6±0.5	

of the neutron deficient species. Cursory inspection of Fig. 1 shows that the distributions of Au fragments are very similar for the three reactions studied in this work. A more detailed examination of the data shows that there is a slight (≤1 u) shift of the distribution centroids toward larger A values as the projectile energy increases. *Thus, although the incident projectile energy changes by over 20 GeV, the excitation energy imparted to target fragments changes by less than 10 MeV.* The ratio of the magnitude of the integrated Au isotopic yields from the 0.40 GeV/nucleon ^{20}Ne bombardment to that from the 0.40 GeV/nucleon ^{12}C bombardment is in rough agreement with the factorization prediction[6] of $\sigma_R(^{20}\mathrm{Ne}+{}^{209}\mathrm{Bi})/\sigma_R(^{12}\mathrm{C}+{}^{209}\mathrm{Bi}) = 3644\ \mathrm{mb}/3030\ \mathrm{mb} = 1.20$. Both of these results are consistent with the observations of Cumming *et al.*[7] who found that the target fragment isobaric and isotopic distributions were identical for many reactions with copper targets.

We are left with the question of whether this apparent saturation in energy transfer is predicted by current models of fragmentation reactions. One highly developed model of such collisions which makes predictions about the fragmentation pro-

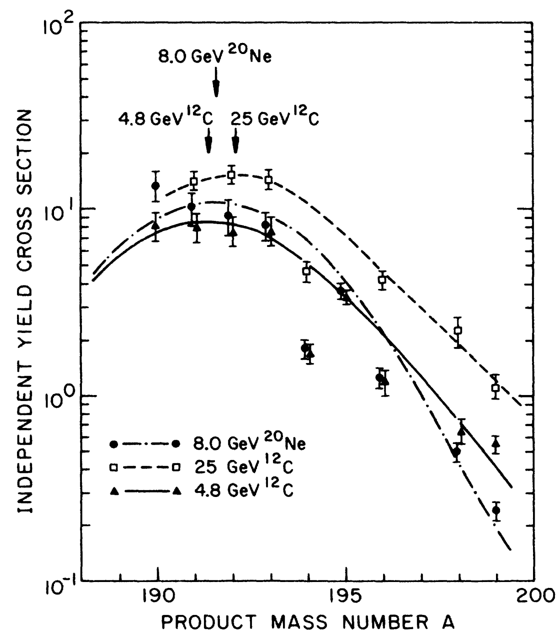

FIG. 1. The isotopic production cross sections for gold products from the reaction of 4.8 and 25.2 GeV ^{12}C and 8.0 GeV, ^{20}Ne with ^{209}Bi are shown. The lines represent the best Gaussian fit to each distribution with the arrows showing the distribution centroids.

ducts is the intranuclear cascade model of Yariv and Fraenkel.[8] In this model the collision process is described by the superposition of a series of nucleon-nucleon collisions with proper accounting of the nucleon-nucleon cross section, angular distributions, Fermi energy distributions, and particle-hole excitations in the fragments before de-excitation. The model calculation does not allow interactions between cascading nucleons and the nucleus is not allowed to rearrange in order to fill the holes created during the fast cascade. The calculated positions of the centroids of the gold isotopic distributions using this model are contained in Table I along with the experimental results. The calculations are in approximate agreement with the results of our study but predict values of the centroids of the distributions which are systematically more neutron deficient (~1–2 u) than our data. (The excitation energies of the primary fragments were ~125–150 MeV.) Thus, the experimentally observed limiting fragmentation behavior of high mass nuclei is predicted by this model of relativistic nucleus-nucleus collisions.

What universal feature of RHI reactions is responsible for this behavior? In this case involving very peripheral collisions (impact parameter $b \sim 9$ fm$> R_{Bi} \simeq 7.0$ fm according to firestreak model[10] calculations), it is simply a matter that the predicted changes in the experimental distributions are very small compared to the sensitivity of the experimental measurement. Unfortunately, selection of events involving more central collisions (i.e., fragments where $A_{target} - A_{fragment} \geq 20$) where the changes in the distributions would be larger suffers from the fact that in such events the primary reaction processes are observed by the subsequent de-excitation of the primary fragments.[9] Thus we conclude that although we have picked a relatively favorable case to study, our observation of limiting fragmentation, like that of others, could mean either a saturation in the transferred energy with increasing projectile energy or that changes in the transferred energy that are too small to detect with current techniques of fragment yield measurement.

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