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# HEAVY RESIDUE PROPERTIES IN INTERMEDIATE ENERGY NUCLEAR COLLISIONS WITH GOLD

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**Abstract**

We have measured the target fragment production cross sections and angular distributions for the interaction of 32, 44 and 93 MeV/nucleon argon with gold, and the heavy residue energies for the interaction of 93 MeV/nucleon argon, 35 and 43 MeV/nucleon krypton with gold. The fragment isobaric yield distributions, moving frame angular distributions and velocities have been deduced from these data. This fission cross section decreases with increasing projectile energy and the heavy residue cross section increases. The ratio $v_{\parallel}/v_{cn}$ increases approximately linearly with mass removed from the target.

## I. Introduction

In nuclear reactions induced by projectiles with energies of ~50 MeV/nucleon, one important group of reaction products is the heavy residues. (The term "heavy residue" is taken to denote a large fragment of the target nucleus such that $A_{fragment} \geq 2/3_{target}$). From studies of p-nucleus collisions[1], is has been apparent for over three decades that such products are the most prevalent class of reaction products at projectile energies above 50 MeV. From the general similarity of yield patterns between p-nucleus and nucleus-nucleus collisions[2], it is not surprising to find such trends in nucleus-nucleus collisions. In Figure 1, we show the relative cross sections for fission and particle emission (heavy residue formation) for the interaction of argon with gold as a function of projectile energy. The decreasing importance of fission as an effective nuclear de-excitation path in these reactions can be attributed to the relatively slow (t ~ $10^{15}$ sec) time scale of the fission process compared to typical reaction times.

Having established the relative importance of heavy residue formation in intermediate energy nuclear collisions (Figure 1), we shall turn our attention to the issue of characterizing these residues and seeing what we can learn about intermediate energy nuclear collisions from studying them.

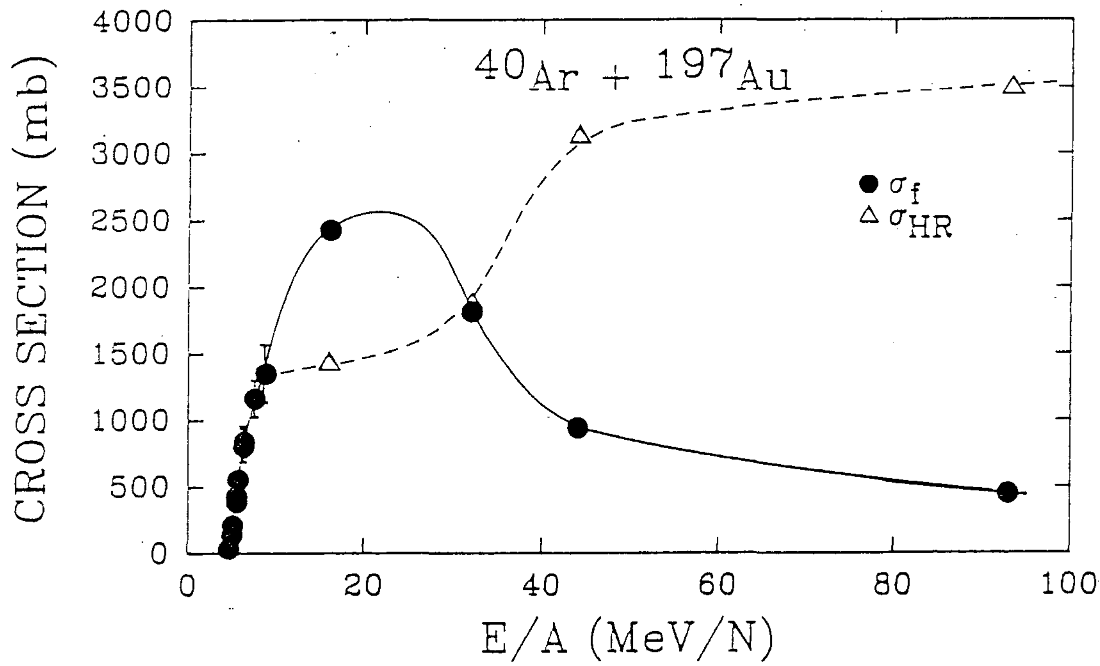


Figure 1. Variation of the fission cross section (solid points) and the heavy residue formation cross section (triangles) with projectile energy for the Ar + Au system.

## II. Experimental Methods.

The heavy residues in p-nucleus and nucleus collisions arise mostly from peripheral collisions. Because of this, they have low energies (< ~ 100 keV/nucleon) for typical reactions of the type "heavy-ion + heavy target nucleus", such as "C, O, Ne, S, Ar, etc. + $^{197}$Au, $^{232}$Th." The combination of the low residue energy and the high Z and A of the residue nuclei in these reactions makes the detection of these reaction products quite difficult. Because of these difficulties, we have chosen to use radiochemical techniques to measure the properties of these fragments. Typical experimental arrangements for measuring heavy residue properties have been described previously[3,4]. The use of radiochemical techniques offers the advantages of: (a) unit Z, A resolution (b) through the use of differential range techniques, the absence of any significant low energy cutoffs in the energy spectra. (c) experimental simplicity which (when combined with economical use of accelerator beams time) allows systematic studies utilizing the facilities of several different accelerators.

A set of typical differential range distributions is shown in Figure 2. Also shown in this figure is the effect of a common velocity cutoff (0.5 cm/ns) upon the observed spectra. Thus, in experiments with such cutoffs, less than 50% of the A = 150 fragments and ~0% of the A = 180 fragments are detected, leading to a very non-representative sample of the heavy residues. For example, radiochemical measurements[5] (which do not have a low energy threshold) of the heavy residue yields in the interaction of 32 MeV/nucleon $^{40}Ar$ with $^{197}Au$ gave a heavy residue production cross section of ~1900 mb while a similar measurement[9] using a time-of-flight spectrometer with a 0.5 cm/ns cutoff gave a cross section of 315 mb.

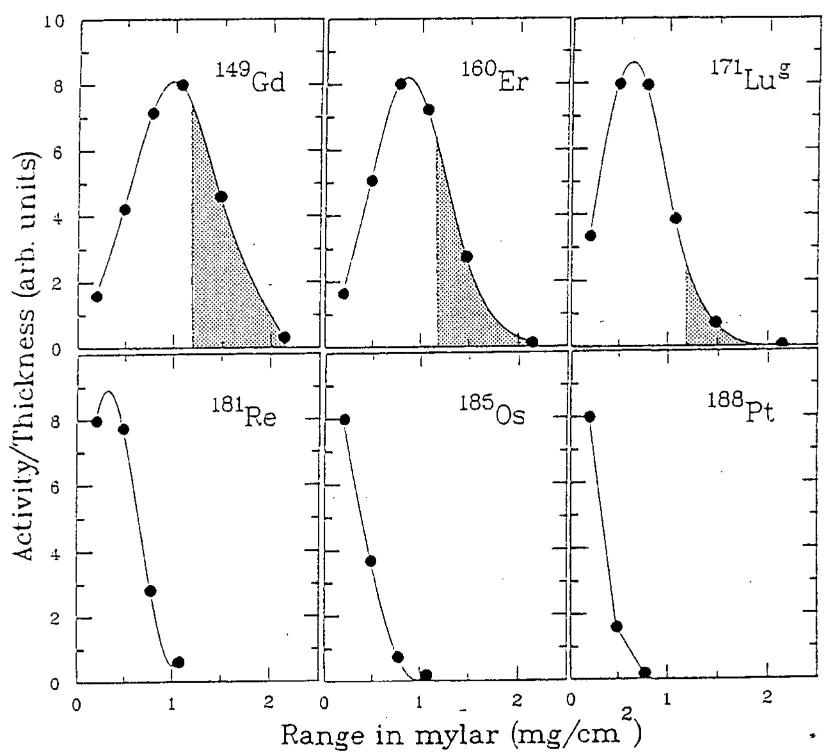


Figure 2. Heavy residue differential range distributions for the interaction of 85 MeV/nucleon $^{12}C$ with $^{197}Au$. The shaded areas represent fragments that would be detected with a 0.5 cm/ns lower velocity cutoff.

A further demonstration of the care that must be taken when measuring heavy residue properties is the comparison (Figure 3) of the indusive fragment mass distribution for the 45 MeV/nucleon $^{12}C$ + $^{197}Au$ reaction (measured using radiochemical techniques[7]) with that measured[8] for the inverse reaction 50 MeV/A $^{197}Au$ + $^{12}C$ using conventional counter techniques. Presumably the small momentum transfers characteristic of heavy residue production were not large enough to allow these fragments to be separated from projectile nuclei in the reverse kinematics experiment.

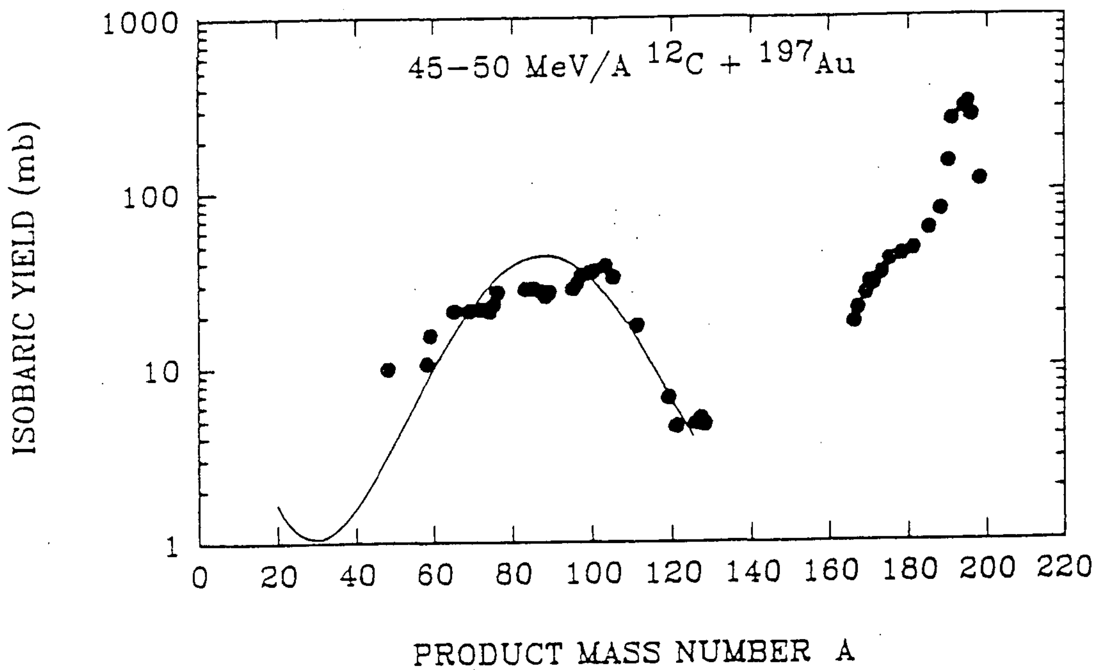


Figure 3. Comparison of the inclusive isobaric yield distributions for the 45 MeV/nucleon $^{12}C$ + $^{197}Au$ reaction (solid points), as measured radiochemically[7] and the 50 MeV/nucleon $^{197}Au$ + $^{12}C$, (solid line), as measured instrumentally[8].

## III. Results and Discussion

<u>A. Mass-yield distributions</u>. The relative importance of different reaction channels and their dependence upon projectile energy is shown for the Ar + Au reaction in Figure 4. At the lowest projectile energies, fission is the dominant de-excitation path for heavy nuclei as represented by the large central bump in the mass distribution. With increasing projectile energy, the centroid of the fission product distribution moves to lower mass numbers reflecting the decreasing mass transfer from the projectile nucleus. At the same time, the

yield of the heavy residues increases (as shown in Figure 1). At the highest projectile energy shown in Figure 4 (93 MeV/nucleon), fission is no longer an easilty discernible component of the mass distribution. The observed fragment isobaric distribution is very similar to the distribution of spallation products seen in relativistic heavy ion reactions. At the higher energies, some indication is also seen for increasing yields of intermediate mass fragments (A<60).

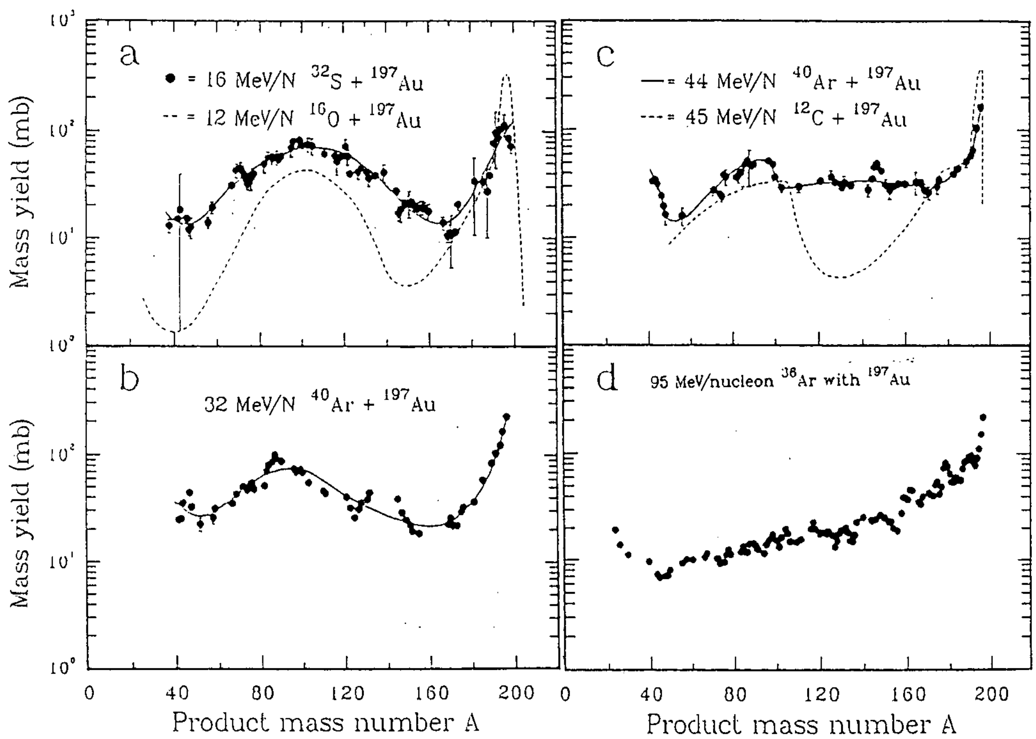


Figure 4. Isobaric yields distributions for the interaction of 16 MeV/nucleon $^{32}$S, 32 and 44 MeV/nucleon $^{40}$Ar and 93 MeV/nucleon $^{36}$Ar with $^{197}$Au.

B. Fragment momentum distributions. A typical set of heavy residue energy distributions are shown in Figure 5. The deduced mean fragment energies are quite low, ranging from 15 keV/nucleon (A=189) to ~300 keV/nucleon (A=131). Even these energies are misleading in that they represent fragment mean energies as observed at ~10°, while the inclusion of larger angle data would lower the mean energies still further.

The first question we might ask ourselves is whether the low mean residue energies, the shapes of the residue spectra and their variation with fragment mass seen in the 85 MeV/nucleon $^{12}$C + $^{197}$Au reaction are consistent with current theories of intermediate

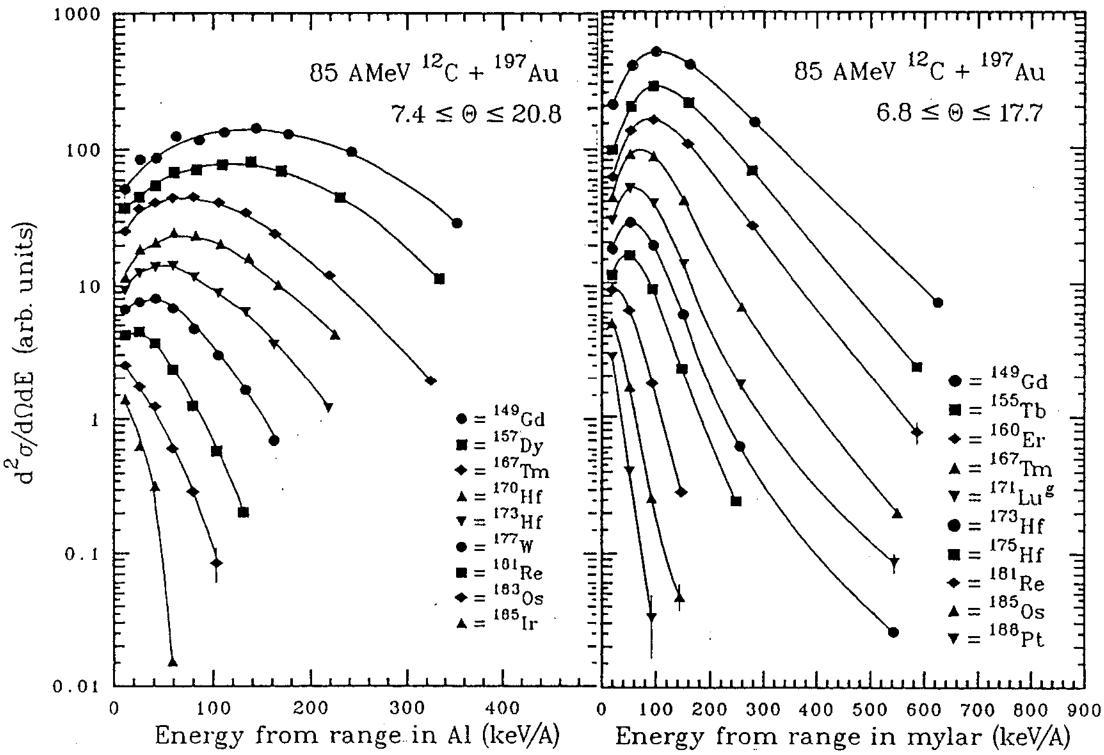


Figure 5. Heavy residue energy spectra for the interaction of 85 MeV/nucleon $^{12}C$ with $^{197}Au$.

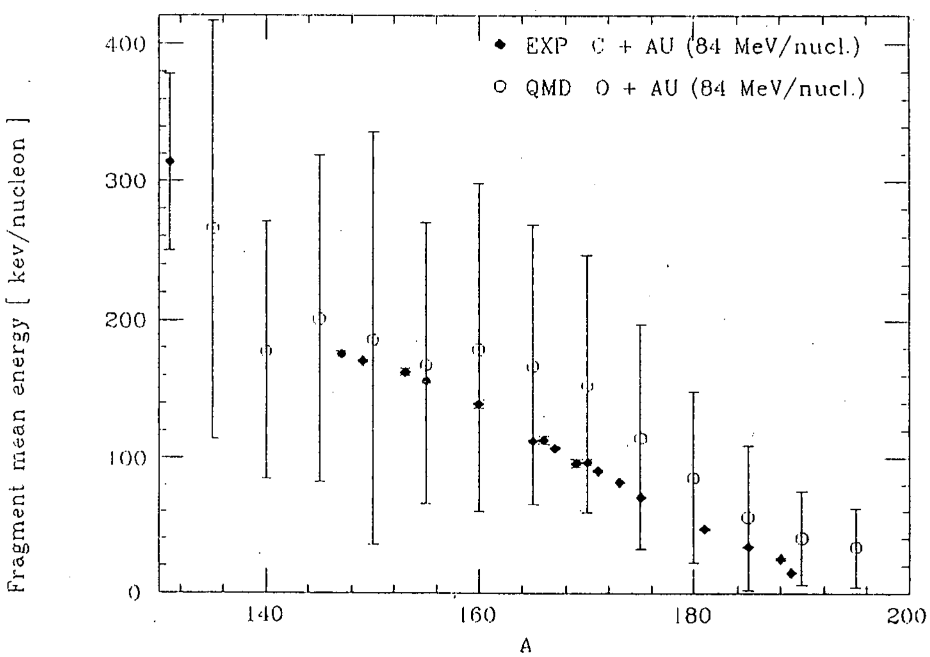


Figure 6. (a) QMD calculation[8] of typical heavy residue mean energies as compared to typical experimental data[4]. The "error bars" on the calculated points represent the calculated spectral widths.

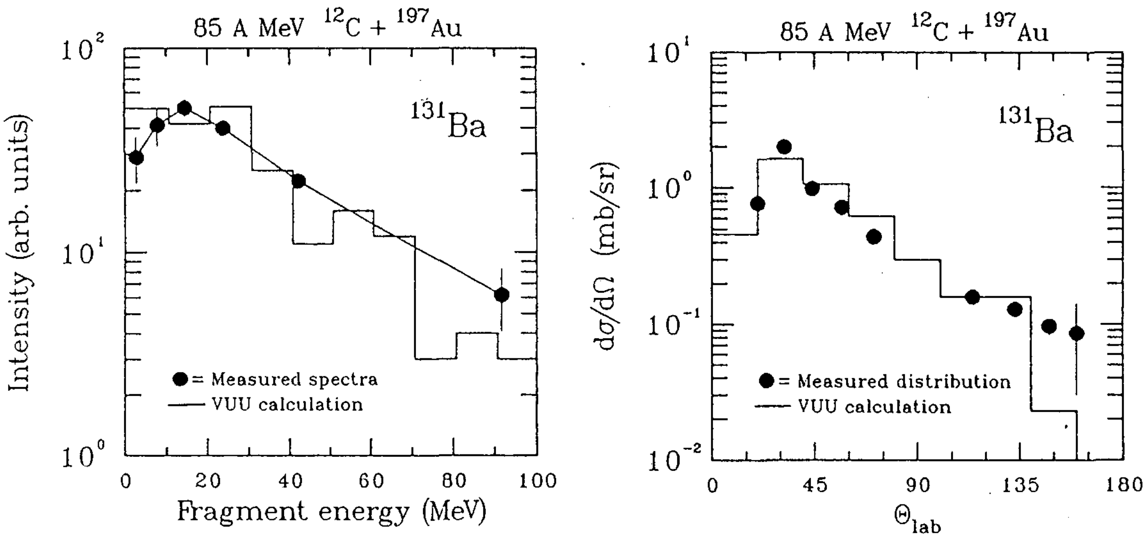


Figure 6. (b) Comparison of VUU calculations (histograms) and measured A=131 fragment energy spectra and angular distributions for the 85 MeV/nucleon $^{12}C$ + $^{197}Au$ reaction.

energy nuclear collisions. The answer to this question seems to be a qualified "yes". QMD calculations[8] predict the correct magnitude and variation of fragment energies with fragment mass (Figure 6a) but grossly overestimate the widths of the distributions. VUU calculations[4], while only having been applied to describe an "average" impact parameter for this reaction, do appear to describe both spectral shape and the residue angular distributions (Figure 6b).

The reaction of 85 MeV/nucleon $^{12}C$ is at the "high end" of the range of intermediate energy nuclear collisions and the successful application of models such as the QMD model to describe the residue properties probably depends upon the "high energy" character of this reaction. The applicability of the QMD model and the apparent similarity between the fragment mass distributions in the reaction of 93 MeV/nucleon $^{36}Ar$ and 1.8 GeV/nucleon $^{40}Ar$ with $^{197}Au$ raises the issue of whether one is seeing "participant-spectator physics" at ~100 MeV/nucleon. The answer to that question seems to be "no" since one finds the average longitudinal momentum transfer in the 93 MeV/nucleon $^{38}Ar$ with $^{197}Au$ reaction to far exceed that seen in relativistic fragmentation (Figure 7a) as does the average rms fragment momenta (Figure 7b).

Thus much of our information about heavy residue momentum distributions seems understandable and in accord with expectations. However, there are certain aspects of the residue momentum distributions that are puzzling and somewhat unexpected. For example, we show (in Figure 8) the variation[11] of the mean heavy residue longitudinal velocity $v_{\parallel}$ (divided by the velocity of the hypothetical compound nucleus $v_{cn}$) with mass loss from the

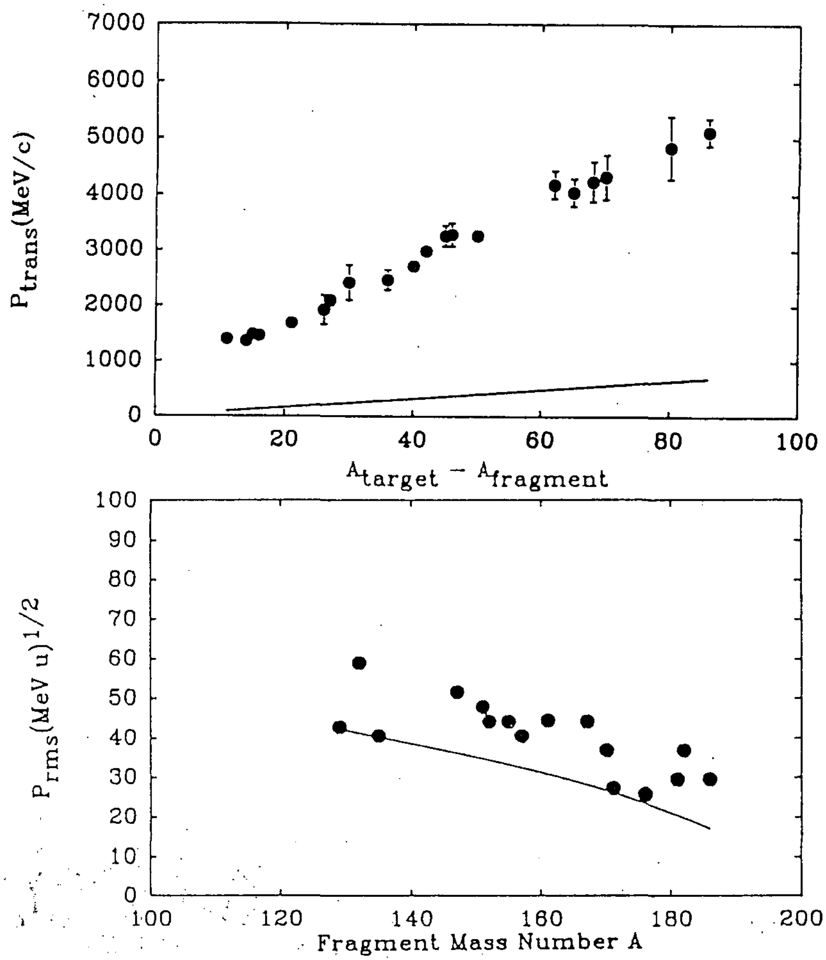


Figure 7. Comparison of the average longitudinal momentum transfer as a function of mass loss for the 93 MeV/A $^{36}Ar$ + $^{197}Au$ reaction (solid points) and that predicted by the systematics[10] of relativistic heavy ion reactions (solid line). (b) Comparison of the average rms fragment momentum (solid points) with relativistic reaction systematics[10] (dashed line).

target nucleus for a series of reactions of carbon, argon and krypton projectiles with $^{197}Au$. Please note that the values of $v_{\parallel}/v_{cn}$ tend to go to zero as $\Delta A$ goes to zero, indicating that no significant fraction of the projectile fused with the target, i.e., the heavy residues resulted from spallation-like events. (The actual values of the zero intercepts are $\Delta A$=-3 and $\Delta A$=-

10 for the carbon and krypton induced reactions, respectively). For the krypton-induced reactions, proximity potential calculations indicate that the fusion cross section is less than 0.5% of the total reaction cross section.

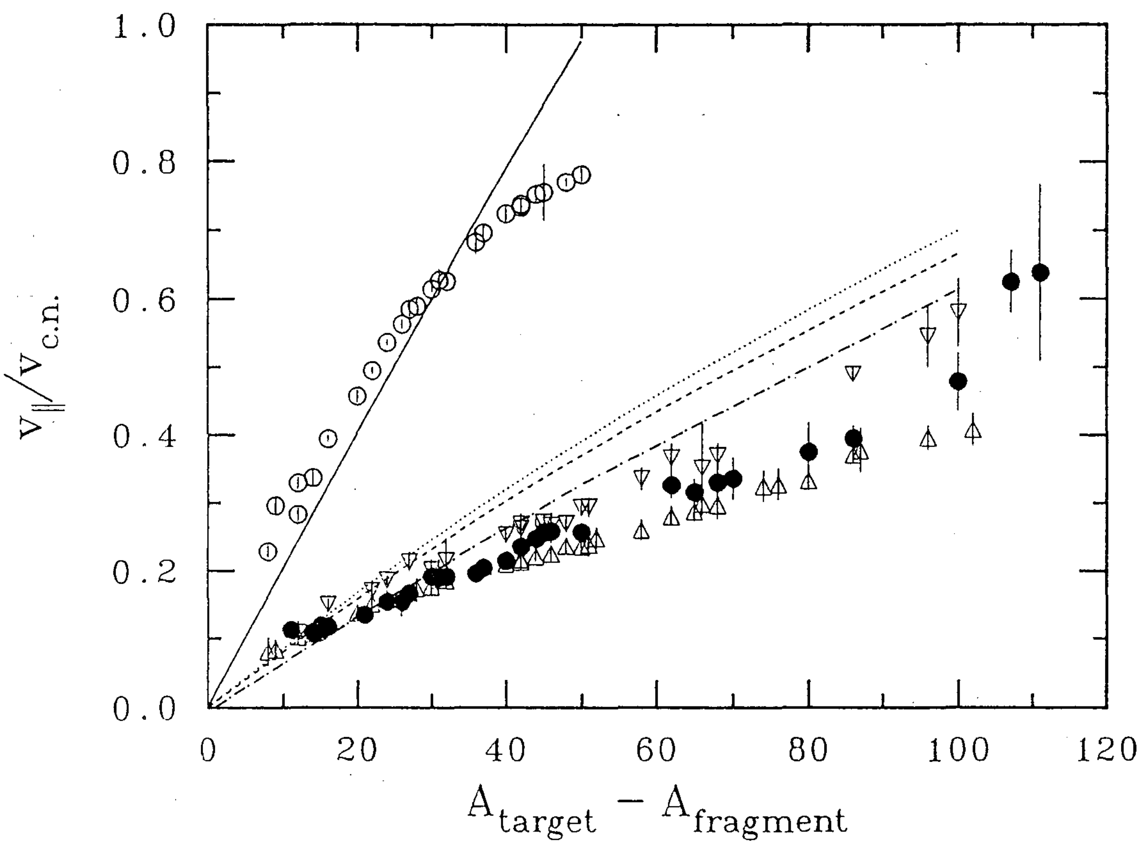


Figure 8. Variation of $\langle v_{\parallel}/v_{cn}\rangle$ for the heavy residue with mass loss from the target nucleus, ΔA. Lines predict eq. (1); open circles and solid line represent 85 MeV/N $^{12}C$ + $^{197}Au$: inverted triangles and dotted line 25 MeV/N $^{84}Kr$ + $^{197}Au$: triangles and dashed line 43 MeV/N $^{86}Kr$ + $^{197}Au$: filled circles and dash-dot line 93 MeV/A Ar + Au.

We arbitrarily divide the data into two groups, the small ΔA and large ΔA events. To understand the data for small mass loss events. We use a general kinematic equation, based upon simple models[10,14] which treat peripheral reactions as quasi-two-body processes. These models all predict a relation of the form

$$\langle p_{\parallel}/p_{cn}\rangle = \Delta E[1+k(1-\beta^2)^{1/2}]/\beta p_{cn}, \qquad (1)$$

where $\beta$ is the projectile velocity, $\Delta E$, the energy transferred to the initial heavy residue (before evaporation), and $p_{\parallel}$, the transferred longitudinal momentum. The parameter k, whose meaning is different in the different models, was found to have a value of ~3 for the production of heavy residues in energetic p-Au collisions[18]. This equation, whose physical content is just kinematics, has been shown to describe all data on projectile and target fragmentation in reactions induced by relativistic protons and heavy ions[10].

If we further assume that the $\Delta E$ term is primarily the excitation energy of the initial heavy residue, E* as $10\Delta A$ where we have assumed that each evaporated nucleon removes 10 MeV of excitation energy[10,16,17]. The straight lines in Figure 8 are the predictions of eq. (1) for $v_{\parallel}/v_{cn}$ with $\Delta A$ for small values of $\Delta A$, i.e., for peripheral reactions. (Some slight improvement would be made in the fit of the model to the data if intercepts corresponding to negative values of $\Delta A$ were allowed, thus simulating the capture of a few projectile nucleons by the target nucleus. Other combinations of values of k and $\Delta E$ could also be used to fit the data.)

Let us consider the events where $\Delta A$ is larger than 20. One sees significant deviations from the behavior predicted by peripheral reaction kinematics. If we use the simple kinematic model of Blachot et al.[18] as a guide, such events correspond to having >55% or >40% of the projectile nucleons being participants in the C and Kr-induced reactions, respectively. These events correspond to "hard" collisions, i.e., collisions at smaller impact parameters in which larger absolute values of the transferred momenta should occur. If we assume these collisions are "hard", we can use the observed values of $\langle v_{\parallel}/v_{cn}\rangle$ to calculate values of $\langle p_{\parallel}/p_{cn}\rangle$, the ratio of the transferred linear momentum to the initial momentum. For a frame of reference, we compare these values of $p_{\parallel}/p_{cn}$ to the extensive systematics of linear momentum transfer in fusion-like events. What one finds is that the maximum fractional linear momentum transfer in the argon and krypton induced reactions is substantially below[11] that expected from the systematics.

How can we explain the relatively low momentum transfer observed for the heavy residues in the argon and krypton-induced reactions relative to the carbon-induced reaction? A possible explanation of this difference involves a limitation in the maximum excitation energy of a nucleus[19]. Using the methods of refs. (19,20), one can calculate the laboratory energy per nucleon at which the critical temperature for the compound nucleus will be reached. For the krypton-induced reactions, $(E/A)_{crit}$ is ~18 MeV/nucleon while for the argon-induced reaction, $(E/A)_{crit}$ is ~36 MeV/A where for the carbon-induced reaction, $(E/A)_{crit}$ ~83 MeV/nucleon. Thus in the reactions of argon and krypton with gold studied in the work, only events with relatively low momentum transfer will allow survival of the heavy residues, while this is not the case in the carbon-induced reaction. Similar conclusions would be reached using the calculational methods of Ngo and Leray[21] who predicted the effect observed in this work. Also it should be noted that this explanation allows for differences in the observed LMT in events leading to fission and heavy residue formation.

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