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Publication Date

1989-06-01

UC-413

LBL-27306 c.1

Preprint

Lawrence Berkeley Laboratory

UNIVERSITY OF CALIFORNIA

Submitted to Physics Letters B

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June 1989

NUCLEAR SCIENCE DIVISION

Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098

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This work was supported in part by the Swedish Natural Sciences Research Council and the U.S. Department of Energy under Grant No. DE-FG06-88ER40402 and Contract No. DE-AC03-76SF00098.

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ABSTRACT: We have measured the heavy residue energies and momenta for the interaction of 35 and 43 MeV/nucleon krypton with gold. The linear momenta of the residues increase approximately linearly with mass removed from the target for small values of ΔA. This agrees with the kinematics of peripheral reactions with small momentum transfer. The momentum transfer in the 43 MeV/nucleon reaction is substantially less than that expected from LMT systematics.

Measurement of the linear momentum transfer (LMT) in intermediate energy nuclear collisions has been an important diagnostic tool for studying the "incompleteness" of the fusion of the projectile and the target nuclei (and thus the reaction mechanism(s) operating). Measurement of the LMT has mostly involved the use of the fission fragment folding angle technique for heavy nuclei and the measurement of the evaporation residue velocities for light nuclei. However, recent investigations[1,2] have shown that for heavy target nuclei, the production of heavy residues($A_{frag}>2A_{targ}/3$) increases in importance with increasing projectile energy and eventually becomes a more important reaction channel than fission. Thus it is important to characterize the LMT using the measurement of heavy residue velocities.

We measured the heavy residue yields, and differential range spectra using radioanalytical techniques for the reactions of 35 MeV/nucleon ^{84}Kr and 43 MeV/nucleon ^{86}Kr with ^{197}Au. A detailed description of the experimental technique is given elsewhere[1]. The experiments were carried out using the GANIL accelerator complex. Well-focussed beams of Kr (~9 mm^2 spot size) struck thin (~240 μg/cm^2) Au targets mounted in the center of an evacuated scattering chamber. Target fragments moving forward in the angular range from 4-17° were stopped in a stack of thin Mylar foils. The Mylar foil stack consisted of 24 foils ranging in thickness from 0.285 to 47.7 mg/cm^2, insuring all fragments of interest were stopped. For the reaction of 35 MeV/nucleon ^{84}Kr with ^{197}Au, target fragment yields were measured in a separate thick target-thick catcher stack consisting of a ~48.6 mg/cm^2 Au foil surrounded by 14.7 mg/cm^2 C foil. Both the thick target-thick catcher stack and the range distribution experiment were irradiated simultaneously. For the 35 MeV/nucleon ^{84}Kr + ^{197}Au reaction study, the the range distribution stack was irradiated for 917 min with an average beam intensity of 6.52x10^{11} ions/min while the irradiation of the thick target-thick catcher foil stack was stopped after 165 min. For the 43 MeV/nucleon ^{86}Kr + ^{197}Au reaction study, the irradiation lasted 780 min with an average beam intensity of 1x10^{12} ions/min. Following irradiation, the foil stacks were disassembled and mounted for off-line gamma ray spectroscopy. Measurements were carried out at GANIL for several days and the foils were shipped to Studsvik and Corvallis for further assay.

From the measured activities, differential range distributions for the 22 and 38 different heavy residues (of known Z and A) were calculated for the 35 MeV/nucleon and 43 MeV/nucleon reactions, respectively. These differential range distributions were transformed into energy spectra using known range-energy relationships. The effect of range straggling and other factors on the deduced energy spectra has been considered elsewhere[1]. The effect of these factors upon the focus of this study, the mean fragment energies, has been shown to be negligible.

In Figure 1, we show the mean residue energies as a function of mass loss from the target nucleus during the reaction for the Kr-induced reactions and the reaction[1] of 85 MeV/nucleon ^{12}C + ^{197}Au. Also shown are the fragment isobaric yield distributions[2,14] for two of the reactions as guides to the relative importance of different mass loss values. Qualitatively, the trend of increasing fragment energy with increasing mass loss from the target (i.e., excitation energy of the target-like fragment) can be understood by saying the smaller impact parameter collisions lead to greater excitation energy (greater mass loss) and increasing fragment energies.

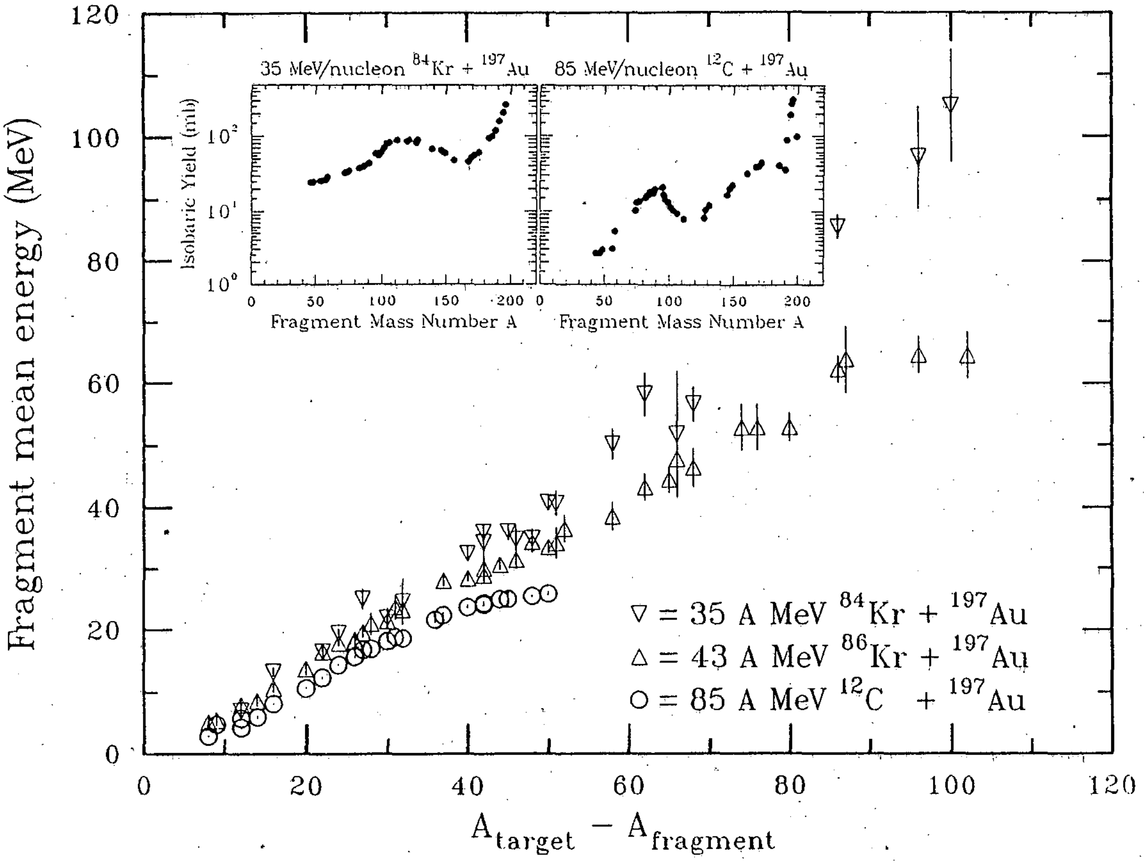

Figure 1. The variation of the heavy residue mean energies with mass loss from the target nucleus, ΔA.

This trend has been predicted by Bondorf et al.[3] who say that this trend can used, within their simple fireball model, to establish the impact parameter leading to a given heavy residue within ±1 fm.

To relate the observations to various models for the reaction mechanism(s) involved, we need to consider a quantity that has not been affected by the particle evaporation that has taken place between the primary residue and the observed residue. Accordingly, we show (in Figure 2) the ratio of the mean longitudinal velocity component, $v_{\parallel}$, to the velocity of the hypothetical compound nucleus, v_{cn}. (Proximity potential calculations[4] for the reactions studied would indicate the

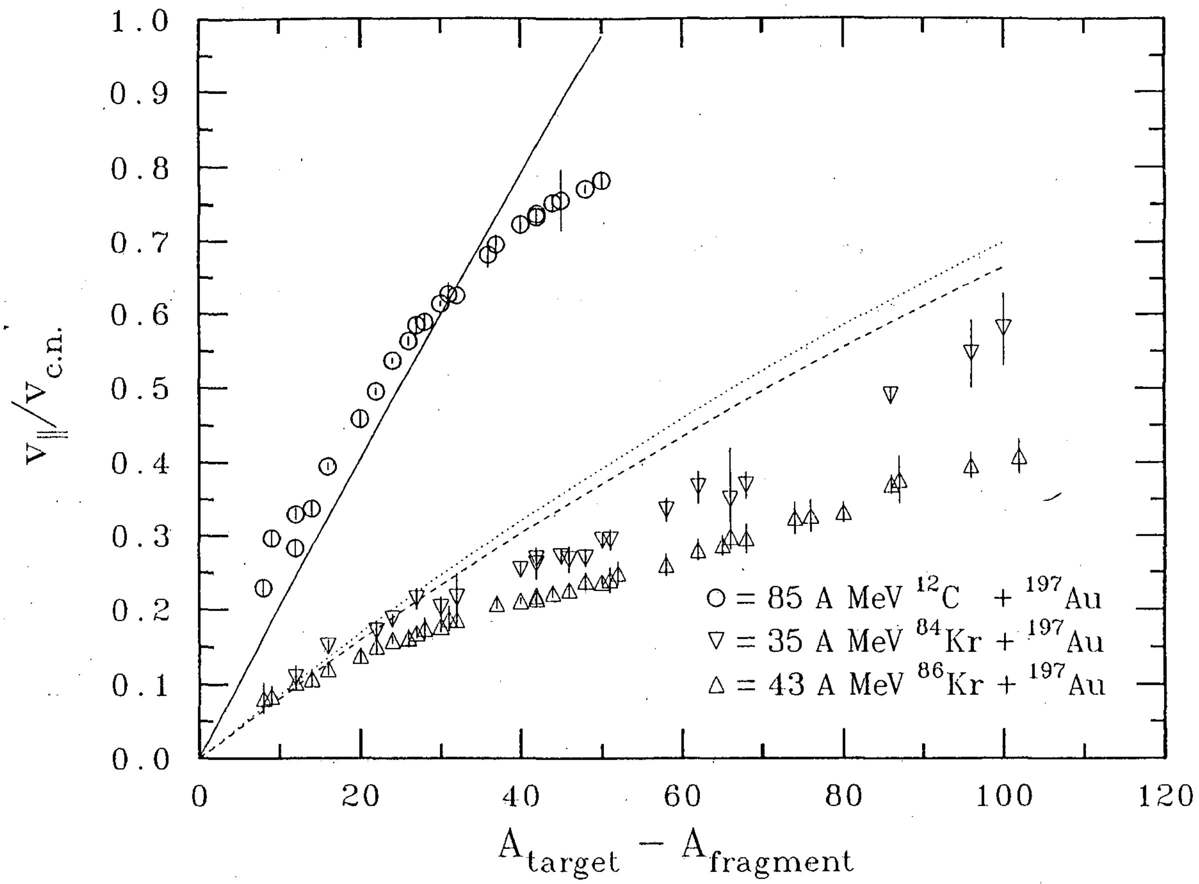

Figure 2. The variation of $\langle v_{\parallel}/v_{cn}\rangle$ for the heavy residues with mass loss from the target nucleus, ΔA. The lines are the predictions of eqn (1) for 85 MeV/N ^{12}C + ^{197}Au (solid line), 35 MeV/N ^{84}Kr + ^{197}Au (dotted line) and 43 MeV/N ^{86}Kr + ^{197}Au (dashed line).

fusion cross section is less than 0.5% of the total reaction cross section.) To understand these data, we use a general kinematic equation, based upon simple models[5-7] 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 β is the projectile velocity, ΔE, 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.[8] If we further assume that the ΔE term is primarily the excitation energy of the initial heavy residue, E^*, then we can approximate ΔE as $10\Delta A$ where we have assumed that each evaporated nucleon removes 10 MeV of excitation energy. The straight lines in Figure 2 are the predictions of eqn (1) for $v_\parallel/v_{cn}$, making the usual massive transfer assumptions to transform $\langle p_\parallel/p_{cn}\rangle$ into $\langle v_\parallel/v_{cn}\rangle$[9]. The essential relationship of the data for the C and Kr induced reactions is reproduced as well as the variation of $v_\parallel/v_{cn}$ with ΔA for small values of ΔA, i.e., peripheral reactions. (Some slight improvement would be made in the fit of the model to the data if intercepts corresponding to negative values of ΔA were allowed thus simulating the capture of a few projectile nucleons by the target nucleus.)

For larger values of ΔA, one sees significant deviations from the behavior predicted by peripheral reaction kinematics. One can rule out the possibility that this limiting behavior of the fractional linear momentum transfer (FLMT), i.e., $v_\parallel/v_{cn}$, is due to the formation of these fragments by fission. Fission would lead to higher rather than lower residue velocities. Furthermore, examination of the fragment mass yield curves and fragment angular distributions for these reactions would show the yields of fission fragments relative to heavy residues to be suppressed at the very forward angles studied in this work. It is interesting to speculate on the interpretation of this possible limiting behavior of the FLMT or at least a different relationship between the FLMT and ΔA than that observed for peripheral reactions.

Firstly, we note that the ΔA values for these events are large. If we assume that each removed nucleon carries away 10 MeV, then these events correspond to excitation energies of 400-1000 MeV. The large values of the excitation energies mean that 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 $<v_{\parallel}/v_{cn}>$ to calculate values of $<p_{\parallel}/p_{cn}>$, the ratio of the transferred linear momentum to the initial momentum. For the largest value of ΔA observed for the three reactions shown in Figure 2, we get values of $<p_{\parallel}/p_{cn}>$ of 0.76, 0.49, and 0.32 for the reactions induced by 85 MeV/A ^{12}C, 35 MeV/A ^{84}Kr and 43 MeV/A ^{86}Kr, respectively. The "universal" systematics of fractional linear momentum transfer[9] would predict values of $<p_{\parallel}/p_{cn}>$ of 0.40, 0.70, and 0.64, respectively. Thus the maximum FLMT observed in the C-induced reaction exceeds the most probable value from FLMT systematics but the maximum FLMT for the Kr-induced reactions is substantially less than the predicted most probable value.

Previous studies utilizing the fission fragment folding angle technique[13] of the linear momentum transfer in the reaction of 25-45 MeV/nucleon ^{84}Kr with ^{232}Th show that at a projectile energy of 43 MeV/nucleon, the predominant linear momentum transfer is small, ~700 MeV/c, with no clear-cut observation of large momentum transfers. This result is in agreement with our heavy residue data. At a projectile energy of 35 MeV/nucleon, both a peripheral and a central collision peak are observed in the folding angle distribution. The central collision peak corresponds to an average linear momentum transfer of 13.0 GeV/c, a factor of ~1.5 greater than the corresponding (ΔA~80) mean momentum transfer observed in the heavy residue spectra. Such high momentum transfers are observed in the heavy residue spectra for ΔA~80 (the expected ΔA value for these large transfer events.) Such events are in the tails of the heavy residue spectra where they cannot be distinguished from fission events in this measurement.

We think this failure to observe large values of the FLMT for large ΔA events in the heavy residue spectra for the 43 MeV/nucleon Kr-induced reactions (or in the folding angle distributions) shows the "universal" linear momentum transfer systematics for central collisions are not universal. They do not appear to hold for a very energetic massive projectile like Kr.

We believe that this failure of the most energetic Kr-induced reactions to follow the linear momentum transfer systematics can be explained by the same concepts used to explain the LMT systematics. Vandenbosch[10] and Gregoire and Scheuter[11] have pointed out the primary effect that defines the LMT systematics is a phase space effect. Only those projectile nucleons with Fermi momenta such that they can be captured into the potential well of the target nucleus are captured and transfer their linear momentum to the target nucleus. These nucleons come into the target nucleus and are reflected off the "back wall" of the target potential well and are captured (a one-body dissipation effect). With increasing relative velocity of the target and projectile nuclei, the ratio of the overlap region between the target and projectile Fermi momentum spheres to the initial volume of the projectile's Fermi momentum sphere becomes less,i.e., fewer projectile nucleons are captured. Fusion becomes less complete and the FLMT decreases. While other effects may also be operating in defining the decrease in FLMT with increasing projectile velocity, this one body dissipation effect is thought[10,11] to be the dominant effect. Such a mechanism also predicts the "universality" of the FLMT systematics because the momentum transfer is independent of projectile and target combinations.

We speculate that with a large projectile like Kr at higher projectile energies, too many projectile nucleons are entering the target nucleus at once and the "back wall" of the target potential well is destroyed leading to minimal capture of projectile nucleons. Such an effect would not appear in Boltzmann master equation calculations[12] which generally describe the "universal" FLMT systematics because such calculations do not include mean field effects which cause what is happening. If this explanation is correct, such an effect should be predicted by VUU or Landau-Vlasov calculations which do include mean field effects. Despite the difficulty of doing such calculations for the large numbers of nucleons involved, the results would be quite interesting.

We gratefully acknowledge the assistance of J. Eriksen during the experiments. Dr. C. Detraz of GANIL has our thanks for providing us with discretionary beam time at GANIL for part of these experiments. Helpful discussions with P.J. Siemens, D.J. Morrissey and V.E. Viola are much appreciated. This work was supported in part by the Swedish Natural Sciences Research Council and the U.S. Dept. of Energy under Grant No. DE-FG06-88ER40402 and Contract No. DE-AC03-76SF00098.

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