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ABSTRACT: We have measured the heavy residue energies and velocities for the interaction of 35 and 43 MeV/nucleon krypton with gold. The ratio $v_{\parallel}/v_{cn}$ increases approximately linearly with mass removed from the target for small values of ΔA, agreeing with the kinematics of peripheral reactions. For large values of ΔA, the maximum momentum transfer in the Kr-induced reactions is substantially less than that expected from LMT systematics, possibly due to limitations on the maximum excitation energy a composite nucleus can sustain.

Measurement of the linear momentum transfer (LMT) in intermediate energy nuclear collisions has been an important diagnostic tool for studying the reaction mechanism(s) involved in these collisions. Measurement of the LMT has mostly involved the

use of the fission fragment folding angle technique for heavy nuclei. However, recent investigations[1,2] have shown that for heavy target nuclei, the production of heavy (or "evaporation") 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 (at 4-17°) 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. In the studies of both reactions, the total particle fluence was 6-8 x 10^{14} particles.

From the measured radioactivities, 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[3]. 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 fragment mass number for both the Kr-induced reactions and, for comparison, the reaction[1] of 85 MeV/nucleon ^{12}C + ^{197}Au. The fragment isobaric yield distributions[4] for two of the reactions are shown also as guides to the relative importance of different mass loss values. (For the ^{12}C induced reaction, the overall mass

distribution[4] is shown while for the Kr induced reaction, the distribution of fragment masses at 4-17° is shown.) 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[5-7]. It is interesting to note the relative constancy of the fragment energies despite large changes in projectile mass and energy.

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 formation of 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}. Please note that the values of $v_{\parallel}/v_{cn}$ tend to go to zero as ΔA goes to zero, indicating 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[8] indicate that the fusion cross section is less than 0.5% of the total reaction cross section. For the carbon-induced reaction, incomplete fusion events have been observed.[9]

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[10-12] which treat peripheral reactions as quasi-two-body processes. These models all predict a relation of the form

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

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.[13] This equation, whose physical content is just kinematics, has been shown[16] to describe all data on projectile and target fragmentation in reactions induced by relativistic protons and heavy ions.

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.[14-16] The straight lines in Figure 2 are the predictions of eqn (1) for $v_{\parallel}/v_{cn}$, making the usual assumptions to transform $\langle p_{\parallel}/p_{cn}\rangle$ into $\langle v_{\parallel}/v_{cn}\rangle$[17]. 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., 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 ΔA were allowed thus simulating the capture of a few projectile nucleons by the target nucleus. Other combinations of values of k and ΔE could also be used to fit the data.)

Let us consider the events where ΔA is larger than 20. One sees significant deviations from the behaviour predicted by peripheral reaction kinematics. One can rule out the possibility that this limiting behaviour of the fractional linear momentum transfer (FLMT) is due to the formation of these fragments by fission. Examination of the fragment mass yield curves (Figure 1) shows the yields of fission fragments relative to heavy residues to be suppressed at the forward angles studied in this work.

If we use the simple kinematic model of Blachot et al.[5] 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[17] in fusion-like events(Figure 3) which summarize previous work. Strictly speaking such a comparison is inappropriate since we do not have fusion-like events for the krypton-induced reactions, but such comparisons are often used in intermediate energy reactions where fusion is not occurring. For the largest value of ΔA observed for the three reactions shown in Figure 2, we get values of $\langle p_{\parallel}/p_{cn}\rangle$ 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[17] (FLMT) would predict values of $\langle p_{\parallel}/p_{cn}\rangle$ 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. This indicated to us that the momentum transfer in Kr-induced reactions (compared to C-induced reactions) is unusually low. As a further illustration of this point, we show (Figure 3) calculated values of the FLMT for these reactions using the pre-equilibrium model of Blann[18]. This model which has been very successful in predicting FLMT in intermediate energy heavy ion reactions can be taken as representative of a diverse class of pre-equilibrium models for FLMT.[19] The disagreement between the predictions and the measurements is further evidence that the heavy residues from the Kr-induced reactions do not follow the LMT systematics.

Previous studies of the linear momentum transfer utilizing the fission fragment folding angle technique[20] 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. Although such high momentum transfers are observed in the tails of the heavy residue spectra for ΔA~80 (the expected ΔA value for

these large transfer events.) no distinct high velocity peak was observed.

How can we explain the relatively low momentum transfer observed for the heavy residues in the 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.[21] Using the methods of ref. 21-22, 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 whereby for the carbon-induced reaction, $(E/A)_{crit}$ ~ 83 MeV/nucleon. Thus in the reactions of krypton with gold studied in this 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[23] who predicted the effect seen 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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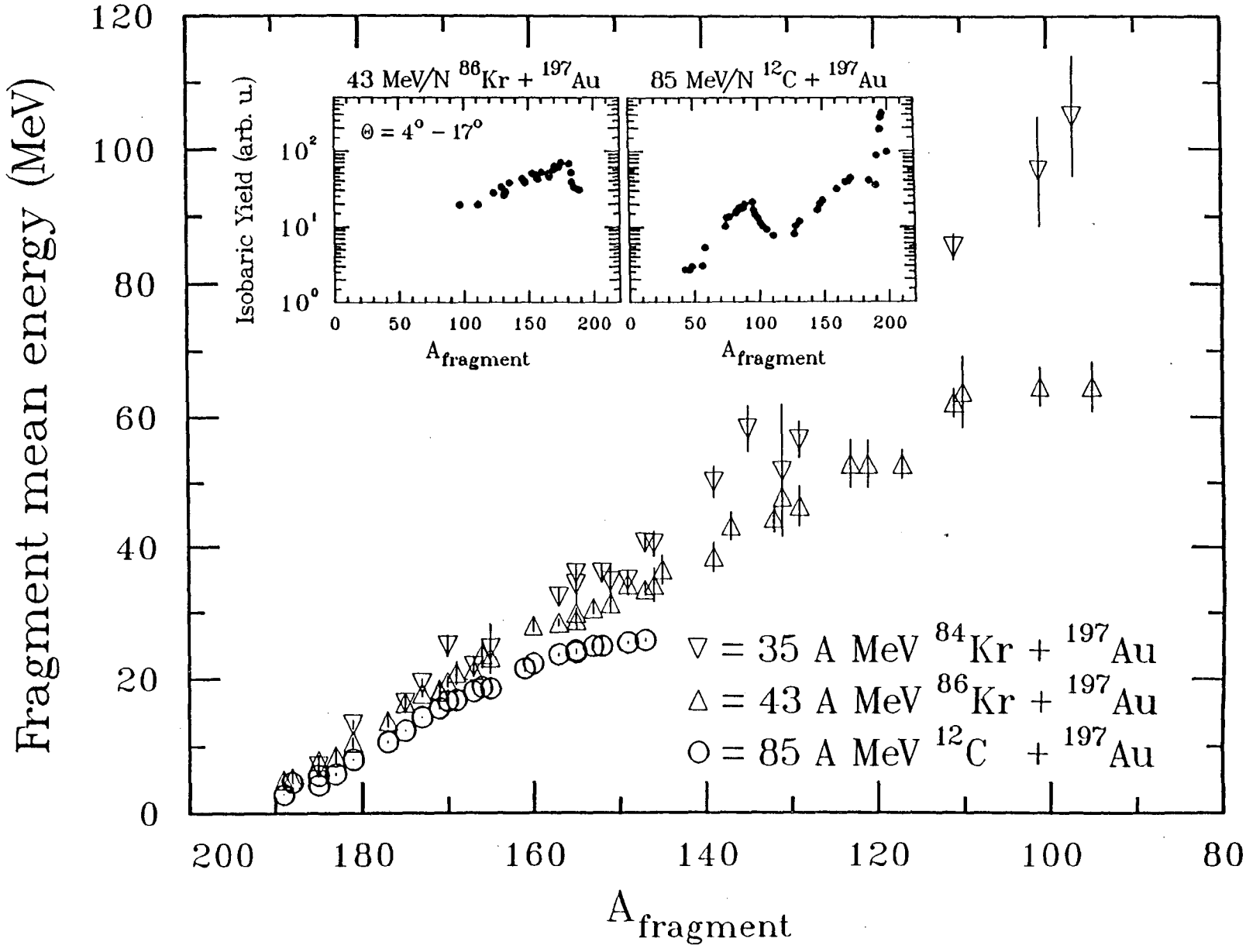
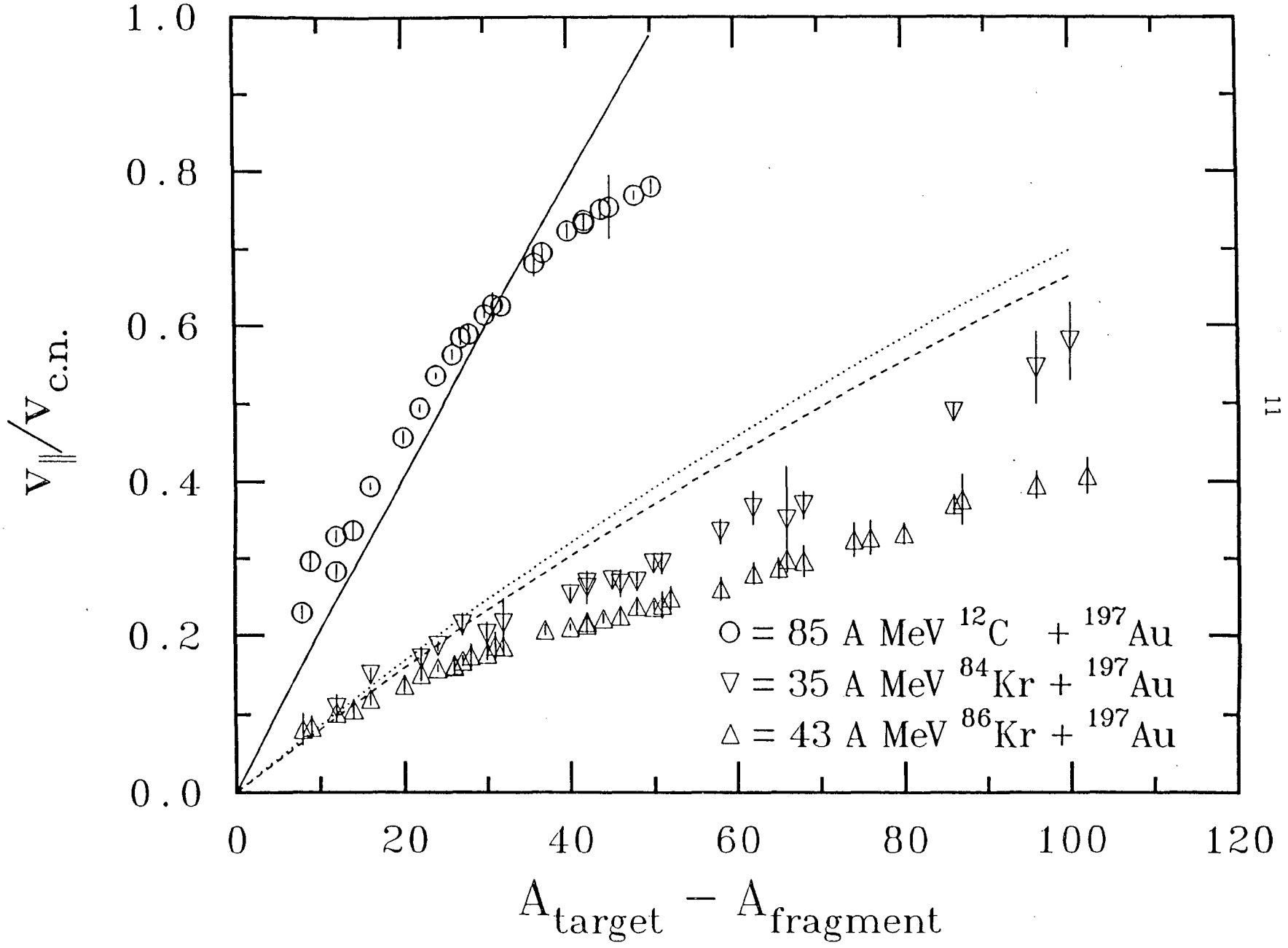
Figure Captions

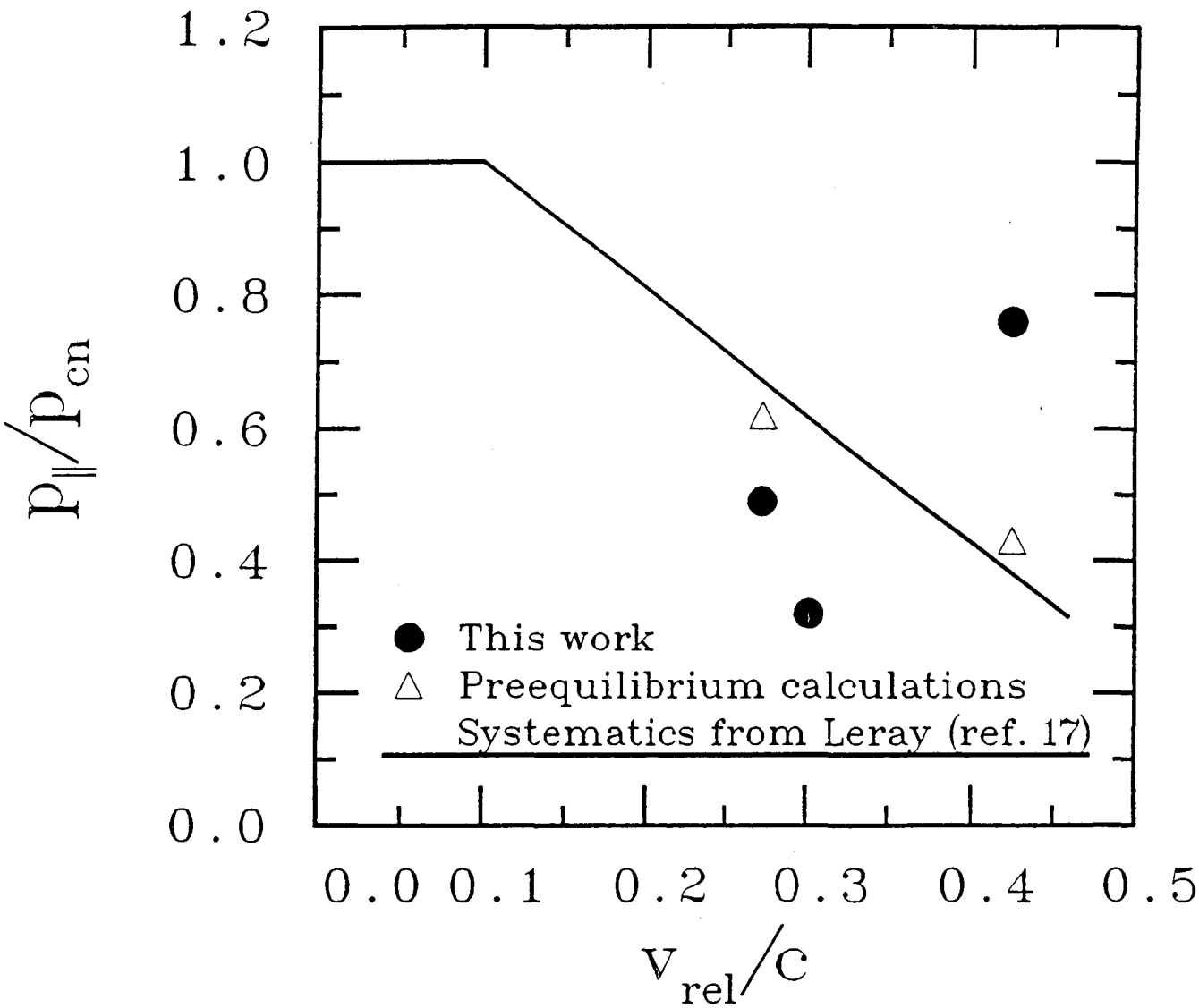
Figure 1. The variation of the heavy residue mean energies with fragment mass number.

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).

Figure 3. The maximum observed fractional linear momentum transfer as a function of the relative velocity of the colliding ions for the systems shown in Figure 2. Also shown are the predictions of a pre-equilibrium model[18] and the systematics[17] of the average fractional linear momentum transfer.


Fragment mean energy (MeV)
A fragment
▽ = 35 A MeV 84Kr + 197Au
△ = 43 A MeV 86Kr + 197Au
○ = 85 A MeV 12C + 197Au
43 MeV/N 86Kr + 197Au
85 MeV/N 12C + 197Au
Θ = 4° – 17°
Isobaric Yield (arb. u.)
A fragment
A fragment


1.0
0.8
0.6
0.4
0.2
0.0
0
20
40
60
80
100
120
$V_{\parallel}/V_{c.n.}$
$A_{target} - A_{fragment}$
○ = 85 A MeV ^{12}C + ^{197}Au
▽ = 35 A MeV ^{84}Kr + ^{197}Au
△ = 43 A MeV ^{86}Kr + ^{197}Au



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