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EVAPORATION RESIDUE CROSS SECTIONS FROM ^{86}Kr BOMBARDMENT OF ^{65}Cu, ^{90}Zr AND ^{109}Ag

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INTRODUCTION

Recent experiments[1,2] have shown that measurements of evaporation residue (ER) cross sections can give important insights on the mechanisms involved in heavy ion reactions. In particular ER cross sections give an unambiguous determination of one portion of the fusion cross section whereas for very heavy ion reactions, measurement of the total fusion cross section (ER + fission) is operationally difficult because of the problems associated with separating compound fission processes from direct fissionlike processes. It has also been shown[3] that measurements of ER mass distributions can be used to provide detailed information on the statistical decay of a fused system.

A major difficulty in the measurement of ER properties is that from very heavy ion beams (e.g. Kr) the ER products are so sharply peaked in the forward direction that they are difficult to observe.[2] In this paper we present the first results from a new experimental system that is capable of measuring ER products to very small angles and of measuring the distributions in M and Z of these products. ER cross sections from ^{86}Kr bombardment of a series of targets are presented and the results compared to calculations from a statistical model[4] of compound nucleus decay which allows for competition between fission and light particle evaporation.

EXPERIMENTAL PROCEDURE

The experiments were performed at the LBL Superhilac using ^{86}Kr beams and self supporting targets of ^{65}Cu, ^{90}Zr and ^{109}Ag which were $\sim$.6 - .9 mg/cm^2 thick. The experimental setup is shown diagramatically in Figure 1. The beam is collimated by two square apertures with widths of 0.10" except for measurements at the smallest angles where widths as small as 0.05" were sometimes used.

Heavy particles from the target were detected at an angle θ and simultaneous measurements were made on their time of flight (TOF), rate of energy loss (ΔE) and residual energy (E). The timing signals were derived by observing electrons emitted from a 25 $\mu g/cm^2$ carbon foil in a chevron channel plate electron multiplier. The ΔE detector was a gas proportional counter and the E detector a standard Au surface barrier detector. This detection system subtended a maximum angle of $\sim 0.4^{\circ}$.

Initial tests of the system with elastically scattered ^{86}Kr ions gave a measured time resolution of $\sim$ 0.4 nsec and an estimated energy resolution of $\sim$ 0.5% with a resultant estimated mass resolution of $\sim$ 1.4%. The $\Delta E \times E$ measurement gives an estimate Z resolution of $\sim$ 4% for Kr ions but the % resolution in the ER region is significantly poorer because of the bunching of the specific ionization curves in this lower MeV/nucleon energy region. With this configuration we found that it was possible to measure ER differential cross sections down to a minimum angle of 1.5° with respect to the beam when the angular acceptance of the detector was stopped down to $\sim 0.2^{\circ}$ and the collimators to 0.05".

Contour plots of ΔE vs. E and E vs. t are shown in Fig. 2 for the ^{86}Kr + ^{65}Cu reaction at 716 MeV and 3° laboratory angle. Figure 2 shows that in both contours the ER products are very cleanly separated from elastic ^{86}Kr ions and the degraded ^{86}Kr ions which result from slit scattering at the collimators. The low peak in Fig. 2 corresponds to elastic ^{86}Kr particles which have been degraded in energy by the Ni support mesh used on the window of the ΔE detector.

The measured ER differential cross sections for 728 MeV ^{86}Kr bombardment of ^{65}Cu, ^{90}Zr and ^{109}Ag are shown in Fig. 3. Absolute cross sections were obtained from normalizing the elastic distribution measured relative to a fixed monitor detector to calculated Rutherford scattering cross sections at a series of angles in the range 5° - 13° for each target. The total ER cross sections are shown for the series of energies and targets in Fig. 4. The error bars show estimated systematic uncertainties in the Rutherford normalization and the extrapolation of $(d\sigma/d\Omega)_{ER}$ to 0°. The point at 620 MeV is from reference 2 for the reaction ^{84}Kr + ^{65}Cu. The estimated ^{86}Kr laboratory energies come from measurements of the attenuated beam in calibrated semiconductor detectors with appropriate corrections for pulse height defect.

DISCUSSION

The measured ER cross sections can be compared with results from a statistical model calculation which estimates theoretically the portion of the fusion cross section which survives fission competition. This calculation[4] includes competition between light particle evaporation and fission using ℓ dependent fission barriers taken from the calculations of Cohen, Plasil and Swiatecki.[5] The qualitative result of this calculation for light nuclei is that fission tends to dominate the deexcitation for high partial waves and evaporation for low partial waves. The evaporation calculations presented in this paper are for the limiting case where the evaporated particles do not change the angular momentum of the system. This gives a lower limit and calculations which allow each evaporated particle to decrease the angular momentum can give considerably higher values for the ER cross sections.

In a previous study[2] of the compound system ^{149}Tb formed in the reactions ^{40}Ar + ^{109}Ag and ^{84}Kr + ^{65}Cu, we found that these calculations were in reasonable agreement with the experimental data for the ^{40}Ar reaction at energies above $\sim$ 200 MeV and for the ^{84}Kr reaction at 620 MeV. In Fig. 4, we show a comparison of the theoretical calculation with measured ER cross sections for the cases investigated in this experiment. In this comparison we see that for ^{86}Kr energies above $\sim$ 500 MeV the calculations for the S-wave lower limit are consistently somewhat lower than the experimental measurements on the ^{65}Cu target. Thus, this model seems capable of qualitatively reproducing the experimental results for this case. For the 370 MeV ^{86}Kr + ^{65}Cu reactions the experimental results are below the calculated lower limit and it seems likely that quasielastic reactions or other entrance channel effects are taking some of the cross section for partial waves that would normally produce ER products.

In Fig. 4, we also show comparisons between calculations and measurements of ER cross sections as a function of the fissility parameter, Z^2/A, for ^{86}Kr bombardment at 728 MeV. In this comparison we see that, while the ER cross section for the ^{65}Cu target is $\sim$ 1.3 times the calculated lower limit, for ^{90}Zr and ^{109}Ag the experimental results have decreased to $\sim$ .75 and $\sim$ .30 of the calculated limits, respectively. This deviation could arise from either of two general effects: (1) the statistical model may underestimate the fraction of the cross section going to fission or (2) a large fraction of the cross section for partial waves which would normally produce ER products does not lead to fusion but instead is lost to some fast direct process in the entrance channel.

In the calculation for the compound system $^{195}Bi(^{86}Kr + ^{109}Ag)$ the fission barrier for zero angular momentum was taken from experimental trends in this region and the angular momentum dependence was taken as described in Ref. 4. The calculations for this heavy system are also very sensitive to the value for the ratio of level density parameters (a_f/a_n). The curve in Fig. 4 assumes $a_f/a_n = 1.0$. For ^{195}Bi it appears that an increase of a_f/a_n within reasonable limits can give calculated results that agree with the experimental determination. These calculations could be studied in more detail if a good measurement of the equilibrium fission cross section for the $^{86}Kr + ^{109}Ag$ reaction could be obtained. Such a measurement is, however, difficult because of the experimental problems involved in separating equilibrium fission from the direct fissionlike processes.

If the small ER cross sections for the $^{86}Kr + ^{109}Ag$ are due to competition in the entrance channel between fusion, and quasifission or quasielastic processes then we may have indications that these processes compete favorably for low partial waves in this system. Previously it has been shown that these processes account for essentially the entire reaction cross section for the $^{84}Kr + ^{209}Bi$ reaction.[6,7]

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FIGURE CAPTIONS

Fig. 1 Schematic diagram of experimental setup. Key: C-collimator, T-target, FC-faraday cup, CP-channel plate.

Fig. 2 Contour plots of residual energy, E, versus time of flight, t, and residual energy, E, versus rate of energy loss, ΔE.

Fig. 3 Angular distributions for evaporation residue products.

Fig. 4 Evaporation residue cross sections as a function of ^{86}Kr bombarding energy and as a function of Z^2/A for a ^{86}Kr bombarding energy of 728 MeV.

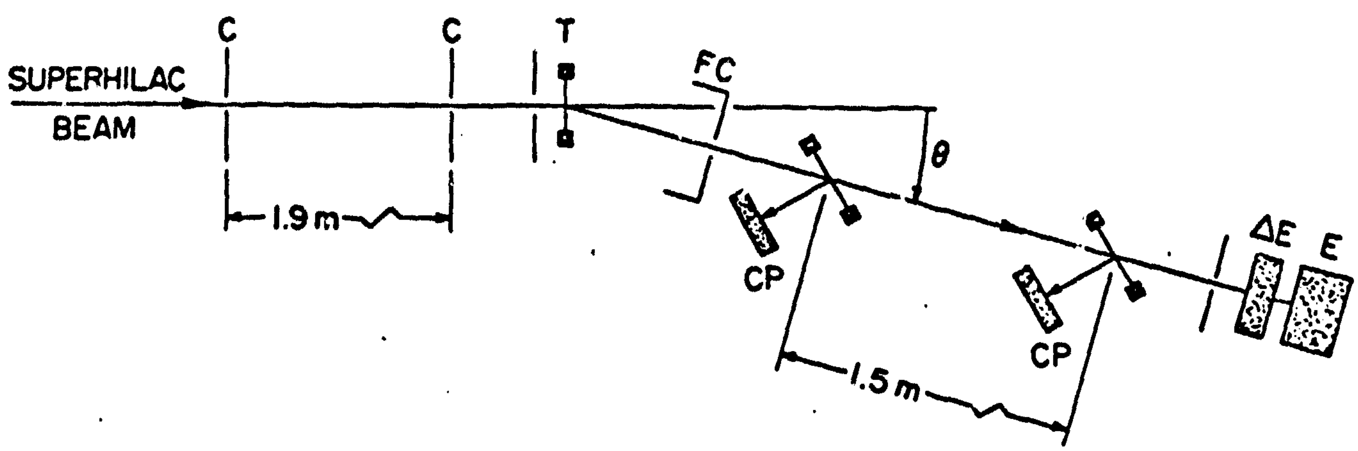
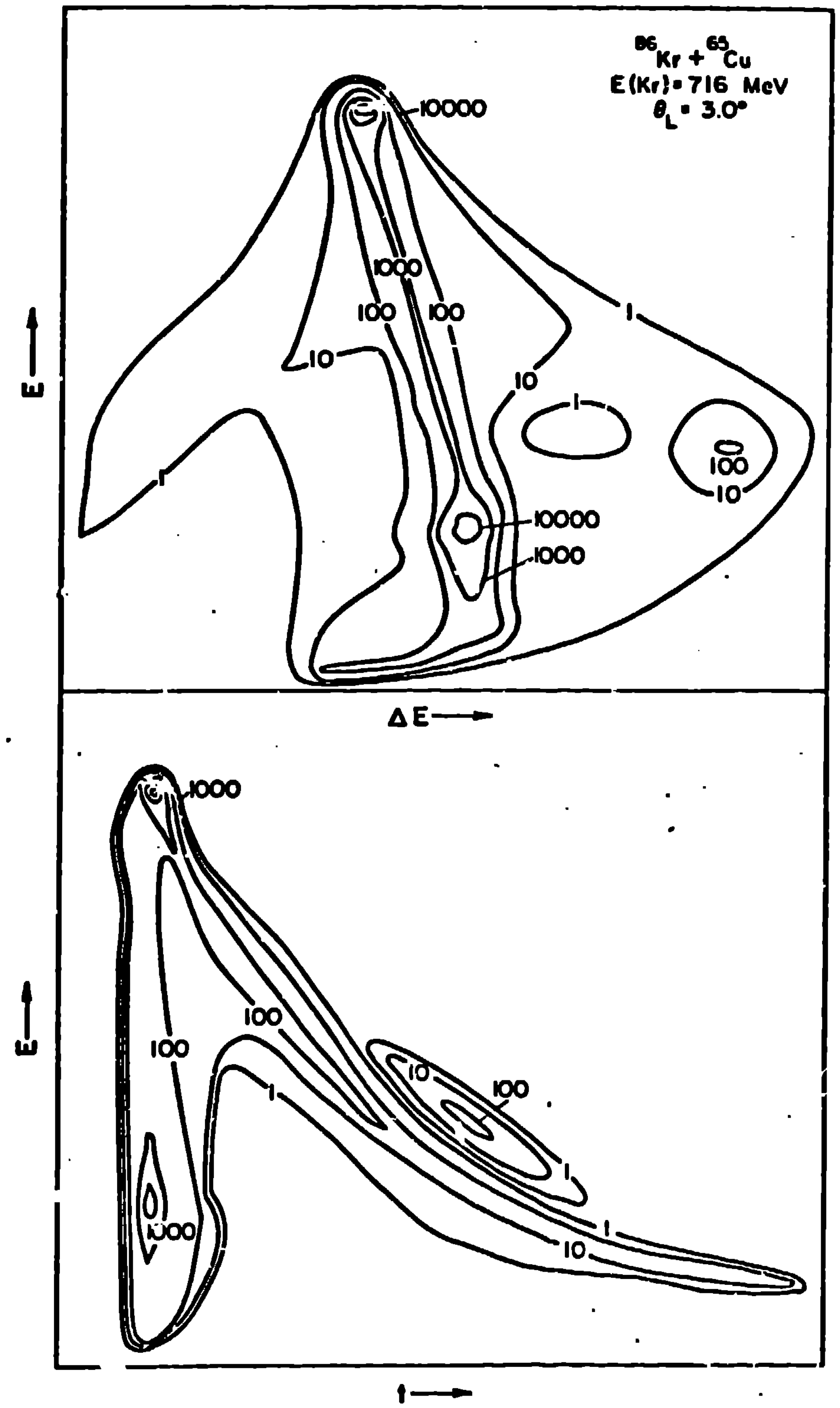


Fig. 1



$^{86}Kr + ^{65}Cu$
E(Kr) = 716 MeV
θ_L = 3.0°
10000
1000
100
100
10
1
10
1
100
10
1
10000
1000
E
ΔE
1000
100
100
10
100
1
1
1
1000
10
E
t

Fig. 2

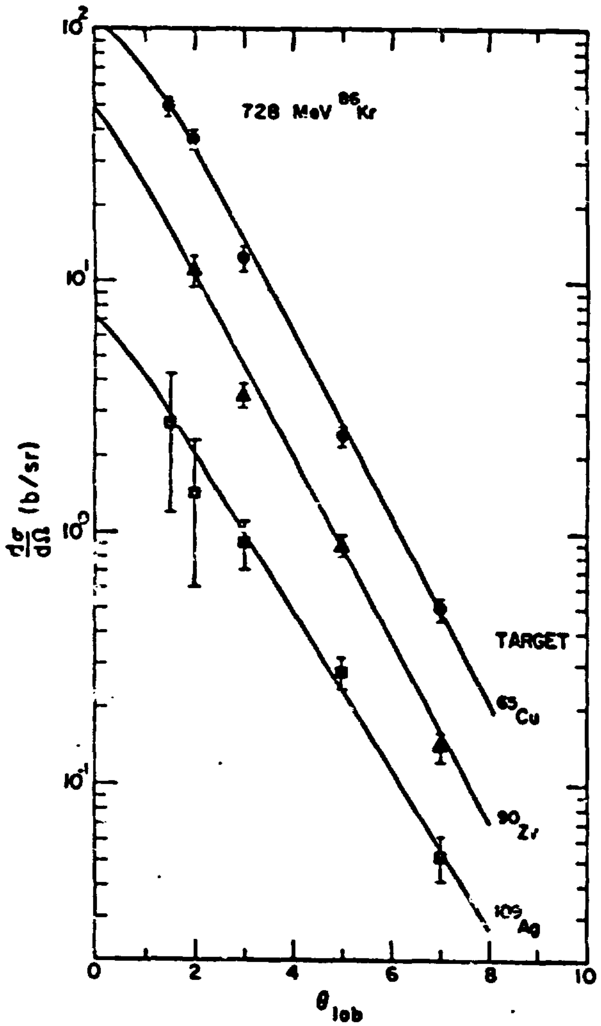

728 MeV ^{86}Kr
TARGET
^{63}Cu
^{90}Zr
^{109}Ag
$\frac{d\sigma}{d\Omega}$ (b/sr)
θ_{lab}

Fig. 3

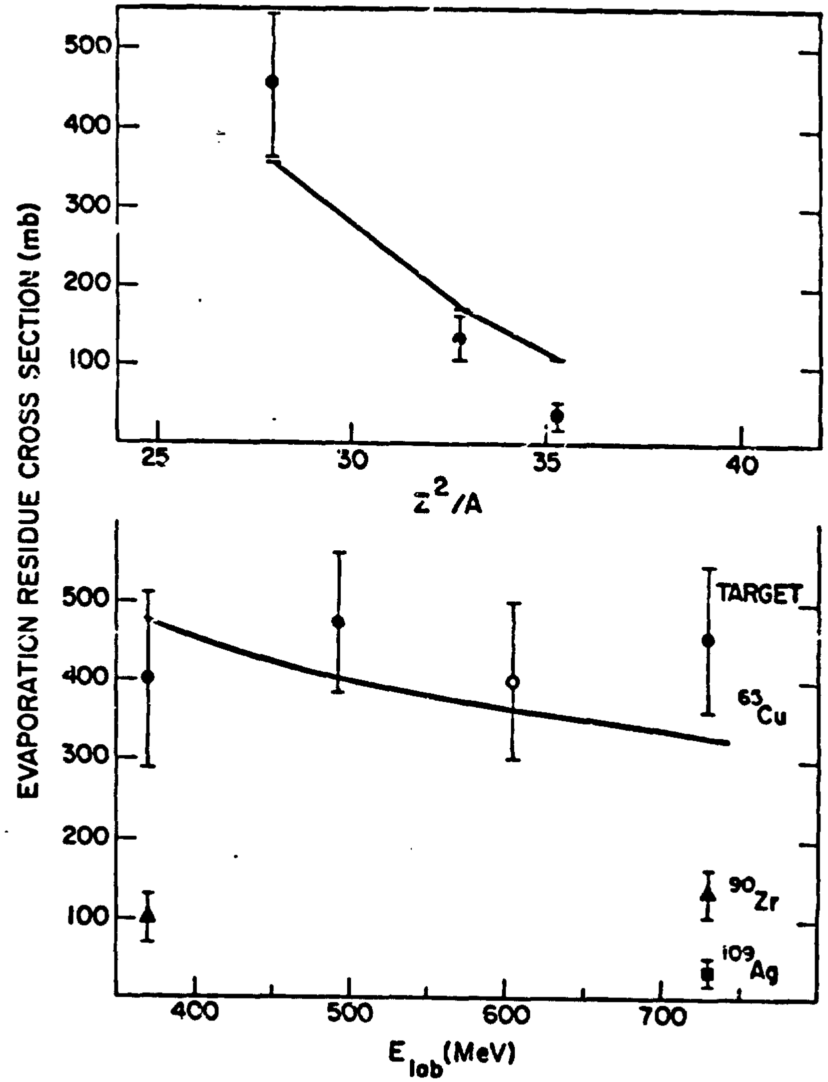

EVAPORATION RESIDUE CROSS SECTION (mb)
Z^2/A
TARGET
^{63}Cu
^{90}Zr
^{109}Ag
E_{lab}(MeV)

Fig. 4