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TRANSITIONAL FEATURES OBSERVED IN THE CHARGE AND ANGULAR
DISTRIBUTIONS OF DEEPLY INELASTIC FRAGMENTS PRODUCED
IN THE REACTION $^{181}\text{Ta} + 620 \text{ MeV } ^{86}\text{Kr}^*$

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ABSTRACT

Charged fragments produced in the reaction $^{181}\text{Ta} + 620 \text{ MeV } ^{86}\text{Kr}$ have been studied with ΔE -E telescopes. Kinetic energy spectra, charge distributions and angular distributions have been measured for atomic numbers in the range $13 \leq Z \leq 49$. For all observed atomic numbers and for all angles, the energy spectra show the presence of energetically relaxed products in the vicinity of the Coulomb barrier. The spectra for elements near the projectile also show a large contribution from incompletely damped events at angles close to the grazing angle. For these elements the spectra show no clean separation between the relaxed and partially damped components. The charge distributions peak at or slightly above the projectile Z. For elements well removed in Z from the

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projectile, the angular distributions are forward peaked, whereas elements near Kr have angular distributions which are side peaked. The transition from side peaking to forward peaking takes place over a smaller range of Z-values than was observed for the reaction $^{197}\text{Au} + 620 \text{ MeV } ^{86}\text{Kr}$. The experimental data are interpreted within the framework of a diffusion model. Angular distributions calculated with the diffusion model are in semi-quantitative agreement with experiment. The coupling between energy dissipation and mass transfer is also discussed.

NUCLEAR REACTIONS $^{181}\text{Ta} (^{86}\text{Kr}, x)$
E = 620 MeV; measured
 $\sigma(E, \theta, Z)$, $13 \leq Z \leq 49$; deduced
charge diffusion constant and
lifetime of reaction intermediate.

1. Introduction

In recent years heavy ion reaction studies have revealed the existence of processes intermediate to direct and compound nucleus reactions¹⁻⁴). Such investigations have encompassed a wide variety of target-projectile combinations — from the very light⁵), like $^{27}\text{Al} + ^{20}\text{Ne}$, to the very heavy⁶), like $^{197}\text{Au} + ^{136}\text{Xe}$. The names attached to these phenomena are almost as numerous as the studies themselves (e.g. deep-inelastic scattering, strongly damped collisions and quasi-fission). As one might conclude from the multiplicity of "labels", the observed characteristics may differ from system to system.

It now appears that these processes can be viewed in a unified way as relaxation phenomena; that is, the observed features are the manifestation of the time evolution of a composite nuclear system (intermediate complex) as it moves, or "relaxes", towards equilibrium along its various modes^{7,8}). Thence, the diverse character of heavy ion reactions may be attributed to different phases in the evolutionary development of the intermediate system. This viewpoint is supported, for example, by the continuous transition in energy damping from the quasi-elastic component to the nearly-thermalized "relaxed" component observed at energies near the Coulomb barrier⁹). The time evolution of other degrees of freedom is also apparent in heavy ion reactions, one of the most obvious being the relaxation of the mass (or charge) asymmetry mode.

Two regimes of mass distributions are apparent in early studies of light systems¹⁰), like $^{107,109}\text{Ag} + ^{40}\text{Ar}$ and of heavy systems³) like $^{209}\text{Bi} + ^{84}\text{Kr}$: in the former case, the charge distributions tend to be broad and "fission-like"; in the latter case, the distributions

are asymmetric, reflecting the entrance channel mass asymmetry. The broad distributions can be attributed to more advanced stages of the relaxation process while narrow distributions can be associated with the early stages in the time evolution of the intermediate complex. The patterns seen in the angular distributions support these conclusions. Broad charge distributions are often accompanied by angular distributions which are forward peaked in excess of the $1/\sin \theta$ distribution expected for compound nucleus decay, indicating that the lifetime of the complex is comparable to the rotational period. Whereas, asymmetric distributions are frequently associated with focused angular distributions, implying that the lifetime is substantially shorter than the rotational period. The transition from side to forward peaking with increasing mass transfer also supports this view¹¹⁾.

Using a model which assumes a diffusive mechanism for the time evolution of the intermediate complex along the mass asymmetry mode, Moretto and Sventek^{7,12,13)} have been able to semi-quantitatively reproduce data from both lifetime regimes (i.e. $^{107,109}\text{Ag} + 288 \text{ MeV } ^{40}\text{Ar}$ and $^{197}\text{Au} + 620 \text{ MeV } ^{86}\text{Kr}$). In this way a charge diffusion constant, the lifetime of the intermediate complex, and information about the potential energy surface have been extracted. Since it is desirable to further test and refine this model and to extend reaction systematics, we have utilized the technique of Z-identification to study a wide variety of target-projectile combinations.

In previous papers we have reported on the results obtained in 620 MeV ^{86}Kr bombardments of Ag and Au targets^{13,14)}. These studies demonstrated that these systems belong to the short- and long-lifetime

regimes, respectively. In order to study the transition between these regimes, we have bombarded targets of intermediate mass (i.e. Tb and Ta) with 620 MeV ^{86}Kr ions. This paper deals with the reaction $^{181}\text{Ta} + 620 \text{ MeV } ^{86}\text{Kr}$.

The next section includes a brief description of the experimental technique and data reduction procedure. Energy spectra, charge distributions and angular distributions are presented in the third section. The fourth part deals with the comparison of the data with predictions of the diffusion model of Moretto and Sventek and a discussion of the energy dependence of the charge and angular distributions. The final section contains a brief summary.

2. Experimental Technique

Self-supporting Ta foils of $.76 \text{ mg/cm}^2$ thickness were bombarded with ^{86}Kr ions produced by the Berkeley SuperHILAC. Charged fragments were detected in any of four ΔE -E telescopes, which were mounted in pairs on opposite sides of the scattering chamber. With these particle telescopes¹⁵⁾, which consist of a gas ionization ΔE and solid state E detectors, it was possible to identify fragments with atomic numbers as high as $Z = 49$. The individual elements appeared as ridges on an E- ΔE contour map. These ridges were located employing an automatic search procedure described elsewhere¹⁶⁾. Gates were then set around each element ridge, and the kinetic energy spectra were projected out. These spectra were suitably corrected for energy losses in the target and the pulse-height defect, and then were transformed to the c.m. system assuming the charge-equilibrium mass¹⁷⁾. The lab and center-of-mass spectra were integrated to obtain laboratory charge distributions and center-of-mass angular distributions. Details of the experimental technique and data analysis procedure have been described elsewhere^{13,14)}.

3. Results

3.1 KINETIC ENERGY SPECTRA

Typical c.m. kinetic energy spectra are shown in fig. 1 for some representative Z-values at four lab angles. In addition, "total" energy spectra are given which were obtained by summing the yield for all elements and making the c.m. transformation with the projectile mass. The high energy cut off for $Z = 36$ in the 10° data is due to the presence of an upper-level discriminator used to cut down the elastic rate. The low-energy tails on spectra for $Z = 36$ and the total spectra are due to slit scattering and low energy, high-Z fragments.

For elements well removed in Z from the projectile (see $Z = 26$ and 46), a single peak is observed at each angle with a mean energy in the vicinity of the Coulomb barrier. These peaks, which are approximately Gaussians, do not exhibit any marked dependence on the angle of observation. The energy spectra for atomic numbers close to 36 do, however, show a dramatic angular dependence. For angles well ahead of the grazing angle like 10° , the spectra consist of a single relaxed component peaked at energies near the Coulomb barrier; however, as the grazing angle (38° in the lab) is approached, the spectra become broader and are shifted to higher energies (see 25°). At angles very near the grazing angle (see 35°), the spectra become quite asymmetric for small mass transfers (like $Z = 34$) and peak at near elastic energies. These high-energy, quasi-elastic events are presumably associated with short interaction times during which only small amounts of mass and kinetic energy are exchanged. At angles well behind the grazing (see 50°), the

quasi-elastic component vanishes and the spectra resemble those at the most forward angles.

The overall dependence of the energy spectra on atomic number and angle for $^{181}\text{Ta} + 620 \text{ MeV } ^{86}\text{Kr}$ is similar to that observed in the reaction $^{197}\text{Au} + 620 \text{ MeV } ^{86}\text{Kr}$ ¹³), and in lighter ion bombardments at energies less than about 1.5 times the interaction barrier ¹⁸). In all these cases it should be noted that there is no clear separation of the relaxed and quasi-elastic components; that is, the spectra show a continuous transition from quasi-elastic to relaxed. This situation is quite different from what one observes in reactions where the incident energy is somewhat higher above the interaction barrier like $^{107,109}\text{Ag} + 620 \text{ MeV } ^{86}\text{Kr}$. In such cases bimodal energy spectra are observed near the grazing angle ^{14,19}).

In fig. 2 average c.m. energies and FWHM's are given as a function of atomic number. These values have been obtained by averaging over the angular range of the measurements excluding the region where a quasi-elastic component is present (i.e. $\theta_{\text{lab}} = 20-40^\circ$ for $30 \leq Z \leq 40$). The "error bars" represent one standard deviation from the mean, and, for the most part, are representative of the experimental uncertainties. The solid curve corresponds to the expected Coulomb repulsion energies for touching spherical fragments ($R = 1.225 (A_1^{1/3} + A_2^{1/3} + 2.0) \text{ fm}$). No rotational energy contribution has been added to this curve, and the experimental points have not been corrected for particle evaporation. Since the inclusion of rotational energy will shift the calculated curve to higher energies and corrections for evaporation will increase the fragment energies above the experimental values (by less than 10%),

one concludes that the fragments are deformed at the moment of scission. This conclusion is consistent with the results of previous studies^{13,14}). The observed energy widths are fairly constant as a function of atomic number (~ 50 MeV), and are similar to those observed for fragments produced in the reaction $^{197}\text{Au} + 620 \text{ MeV } ^{86}\text{Kr}$, but are somewhat larger than those observed for $^{107,109}\text{Ag} + 620 \text{ MeV } ^{86}\text{Kr}$ (~ 35 MeV).

3.2 CHARGE DISTRIBUTIONS

Laboratory charge distributions are presented in fig. 3(a)(b). Representative statistical errors are shown for the 10° , 25° and 30.5° data. These charge distributions were obtained by integrating the energy spectra over all energies, and thus include the contribution of incompletely damped events for atomic numbers near $Z = 36$ at angles close to the grazing angle (38° in the lab). Because it is difficult to identify low-energy high Z fragments, the range of atomic numbers is more restricted at larger angles.

It is apparent from fig. 3 that both the magnitude and shape of the charge distributions depend strongly on the angle of observation. For atomic numbers with $Z < 30$ and $Z > 40$, the yield is concentrated in the forward direction. However, elements near the projectile attain their maximum cross section at about 35° . At forward angles like 10° and 19.5° , the distributions are broad and peak a few Z -units above the projectile. As the grazing angle is approached, a very pronounced peak develops at the projectile Z . The yield for elements near Kr is of course enhanced by quasi-elastic transfer. Note that transfer to and from the projectile occur with roughly equal probability (for small mass transfer). For larger mass transfers a distinct asymmetry about $Z = 36$ is observed. (The dependence of the charge distribution on energy will be discussed in the next section.) The peak at $Z = 36$ diminishes in strength at more backward angles, and the distributions become broad again (39.5° and 44.5°). For 44.5° the yield is essentially constant for $Z \gtrsim 38$. This could be due to the fission of heavy fragments formed by large mass transfers to the target. However, it

seems unlikely that this mechanism alone could account for the observed trend, which is more probably the result of enhanced diffusion toward symmetry²⁰). The charge distributions obtained at the most backward angles (i.e. 55° , 60° , 70° and 80°) are limited in Z-range but appear similar to the 44.5° and 50° data.

The overall pattern of the charge distributions is clear: broad distributions peaked slightly above the projectile at forward angles; distributions sharply peaked at the projectile near the grazing angle; and very broad distributions beyond the grazing, apparently shifted to higher Z's. A similar pattern observed^{11,13}) in the charge distributions for the reaction $^{197}\text{Au} + 620 \text{ MeV } ^{86}\text{Kr}$ has been interpreted in terms of an ℓ -dependent lifetime for the intermediate complex.

Within the framework of this picture, the high ℓ -waves have the shortest lifetimes so that the intermediate complex decays before it has undergone extensive transfer of mass and energy. The short lifetimes allow only small rotation angles. Hence the high ℓ -waves are associated with the narrow distributions near the grazing angle. Intermediate ℓ -values which lead to longer lifetimes, larger mass and energy transfers, can be associated with the broader charge distributions observed at more forward angles. Similarly, the low ℓ -waves can be correlated with the still broader distributions at backward angles. More quantitative comparisons will be discussed later.

3.3 ANGULAR DISTRIBUTIONS

Angular distributions in the c.m. system are shown in fig. 4 for atomic numbers in the range $20 \leq Z \leq 49$. For reference a $1/\sin \theta$ angular distribution is shown. Data for the projectile have been omitted because of serious background problems at forward angles.

As is evident from the figure, the angular distributions exhibit a strong Z-dependence. For atomic numbers well below the projectile Z-value, the angular distributions are peaked strongly in the forward direction well in excess of the $1/\sin \theta$ compound nucleus limit. The usual interpretation of this behavior is that the lifetime of the complex is shorter than its rotational period so that fragments are preferentially emitted in the forward hemisphere. Similar distributions have been observed for elements in the vicinity of the projectile and target Z in "light ion" (i.e. $A \leq 40$) bombardments of various targets^{4,20,21}). As one moves to larger Z-values a slight shoulder appears near 30° (see $Z = 28$). For slightly larger Z-values (e.g. $Z = 30$) the shoulder becomes well developed and it shifts to somewhat larger c.m. angles. At $Z \approx 32$ a peak appears near 45° , whereas atomic numbers adjacent the projectile exhibit a sharp peak at about 50° . (It should be stressed that all energies are included in these cross sections and that the spectra for atomic numbers near the projectile are far from being "relaxed".) For elements above $Z = 36$, the peak diminishes in strength, and eventually disappears around $Z = 44$ or so. The behavior of the angular distributions for the highest observed atomic numbers is similar to those of the low Z-values. In fact, the pattern is rather symmetric about the projectile Z in that the side peaking vanishes for net transfers of more than 8 charge units.

This transition from side peaking to forward peaking can be explained in terms of a diffusion controlled time delay. On the average the diffusion process populates the atomic numbers close to the projectile Z on a shorter time scale than those well removed in Z from the projectile. Since the effective lifetime is short near the projectile, side-peaked angular distributions result. Away from the projectile the longer effective lifetimes allow far more rotation of the complex, thus producing forward peaked distributions. Of course the spread in lifetimes and the ℓ -dependence of the potential can also effect the shape of the angular distributions as will be discussed in the next section.

The pattern of angular distributions for the $^{181}\text{Ta} + ^{86}\text{Kr}$ reaction is qualitatively similar to that observed for $^{197}\text{Au} + ^{86}\text{Kr}$ at the same bombarding energy; however, there are significant differences. In the latter case the side peaking is more persistent. "Pure" forward peaking sets in after the transfer of 12 charge units for $^{197}\text{Au} + ^{86}\text{Kr}$, but only after 8 charge units for $^{181}\text{Ta} + ^{86}\text{Kr}$. Thus a rather small change in the charge (and mass) of the target (less than 10%) has a sizable effect on the angular distributions.

Moretto and Schmitt²²⁾ have proposed that the character of such angular distributions depends on the ratio of the c.m. kinetic energy to the Coulomb barrier (i.e. E/B). More explicitly, side peaking is expected to be more pronounced for E/B values lower than about 1.5. Since this ratio is 1.5 and 1.6 for ^{197}Au and $^{181}\text{Ta} + 620 \text{ MeV } ^{86}\text{Kr}$, respectively, the current experimental data supports the E/B scaling hypothesis (see also^{18,22,23,24)}).

4. Discussion

4.1 DIFFUSION MODEL CALCULATIONS

In this section the experimental data is compared with the diffusion model of Moretto and Sventek^{7,12,13}). This model assumes that the target and projectile nuclei form an intermediate complex in which the mass asymmetry is well defined. The mass transfer process is treated as a diffusion process as governed by the Master equation:

$$\phi_Z(t) = \sum_{Z'} (\Lambda_{ZZ'} \phi_{Z'}(t) - \Lambda_{Z'Z} \phi_Z(t)) \quad , \quad (1)$$

where $\phi_Z(t)$ is the population of configuration Z at time t and $\Lambda_{ZZ'}$ is the macroscopic transition probability coupling the configurations Z' and Z . Equation (1) can be rewritten⁷) in terms of the appropriate level densities, a diffusion constant κ and a geometrical form factor f . The potential energy of the complex is computed from the liquid drop model:

$$V_Z = E_{LD}(Z) + E_{LD}(Z_{tot} - Z) + E_{Coul} + E_{rot} \quad , \quad (2)$$

where the first two terms are the liquid drop energies of the two fragments; E_{Coul} and E_{rot} are the Coulomb repulsion and rotation energies, respectively. For simplicity the fragments are assumed spherical but are allowed to overlap. The distance between centers d is given by

$$d = R_1 + R_2 + \delta \quad (3)$$

where R_1, R_2 are the fragment radii and δ is an adjustable parameter. Some calculated potential energy curves for $^{181}\text{Ta} + ^{86}\text{Kr}$ are given in fig. 5 for

$\delta = -2.0$. One sees that as the angular momentum increases, the potential minimum becomes more pronounced, resulting in a large driving force towards symmetry. This effect is clearly illustrated in the diffusion model calculations of fig. 6, obtained by solving eq. (1) in the Z, t - plane. For $\ell = 0$ the relatively flat potential leads to a very broad Z -distribution. Larger ℓ -values result in progressively narrower Z -distributions since the deeper potential minimum enhances the diffusion towards symmetry. The calculations of fig. 6 are in qualitative agreement with the data. The charge distributions of fig. 3 show a shift toward Z -values above 36 (in the angular range forward and behind the grazing angle) in agreement with the theoretical predictions. The fact that the calculations predict broad distributions for low ℓ -waves and sharp distributions for high ℓ -waves also lends support to the correlation between ℓ -value and lab angle as pointed out in the last section.

In order to make quantitative comparisons with the experimental data, it is necessary to make some assumptions about the distribution of lifetimes $\pi(t, \ell)$ for the complex. It was assumed that

$$\pi(t, \ell) = \frac{1}{N(\ell)} e^{-(t-\tau(\ell))^2/\sigma^2(\ell)} \quad , \quad (4)$$

where $N(\ell)$ is a normalization constant and $\tau(\ell)$ and $\sigma(\ell)$ are given by

$$\tau(\ell) = \tau(0) (1 - \ell/\ell_{\max}) \quad , \quad (5)$$

$$\sigma^2(\ell) = \sigma^2(0) (1 - \ell/\ell_{\max}) \quad , \quad (6)$$

where $\tau(0)$ is the mean lifetime and $\sigma(0)$ is the spread in the lifetime for $\ell = 0$. A direct comparison between the calculated angle-integrated charge distribution and the experimental values is presented in fig. 7. The following values of the parameters were used in this calculation:

$$\tau(0) = 35. \times 10^{-22} \text{ sec},$$

$$\sigma(0) = 10. \times 10^{-22} \text{ sec},$$

$$\kappa = .5 \times 10^{+21} \text{ fm}^{-2} \text{ sec}^{-1},$$

$$\delta = -2.0 \text{ fm}.$$

These values* were used initially because they had previously yielded good agreement with the experimental angular distributions for the system $^{197}\text{Au} + ^{86}\text{Kr}$.

The experimental values in fig. 7 were obtained by integrating over the experimental range of measurements. Because of the limited angular range of the measurements, a sizable fraction of the cross section may be missed, particularly for high Z-values. As is seen from the figure, the fit to the low Z data (i.e. $Z \gtrsim 31$) is quite good. Both the magnitude

*The value for $\tau(0)$ differs slightly from that given in ref. 13 where there was an inconsistency in the moment of inertia $\mathcal{J}$ used in the calculations. Using a consistent value of $\mathcal{J}$, it was necessary to adjust $\tau(0)$ slightly ($\approx 10\%$) to obtain essentially the same fits. However, the lower value of $\tau(0)$ does not change any of the conclusions in ref. 13.

and slope of the cross section is reproduced within 30%. Although near $Z = 36$ the theory grossly underestimates the cross section, this failure is not unexpected since the energy spectra clearly show a large contribution of incompletely damped events for these elements. The theory is not really applicable in this region since the overlap parameter δ and the form factor f have been held constant for all ℓ -values ($f = 2\pi R_1 R_2 / (R_1 + R_2)$) as in ref. 7). Both of these quantities are expected to decrease for high ℓ -waves. Since the theory does not take this into account, the highest ℓ -waves have been left out of the calculations ($P(\ell) = .5$ for $\ell \approx 250$). The fit to the high Z data (i.e. $Z > 36$) is rather poor. The theoretical values are almost a factor of two larger than the experimental numbers around $Z = 40$. However, if one extrapolates the experimental data using the shapes of the theoretical angular distributions, the discrepancy is reduced to about 30%.

A more rigorous test of the diffusion model calculations is given in fig. 8 where an absolute comparison is made between the experimental and calculated angular distributions. The same values of the parameters given above were used in these calculations. The agreement is quite good. Both the magnitude and shape of the angular distributions are very accurately reproduced for the high Z 's (see $Z = 39 - 45$). For Z 's near the projectile, of course, the peak magnitude is grossly underestimated due to the omission of the quasi-elastic component in the calculations. Nevertheless, the agreement at angles well removed from the grazing angle is reasonable, in particular the slope of the fall-off at backward angles is correctly predicted for $Z = 35$ and 37 . The agreement with the data for Z 's below the projectile is less satisfactory.

For $Z = 25$ and 27 the experimental angular distributions show stronger forward peaking than the calculations predict. In addition, the behavior at backward angles is not reproduced by the model: while the data shows some evidence of backward peaking (perhaps due to orbiting), the calculations decrease monotonically with increasing angle.

The effects of varying $\tau(0)$ and $\sigma(0)$ are illustrated in fig. 9. The first and third columns show the effect of varying $\tau(0)$ (the second column repeats some of the calculations of fig. 8). For $\tau(0) = 45^*$ one sees that the side peaking has almost vanished, leaving a small shoulder for $Z = 35, 39, 43$. The loss of side peaking is due to the fact that, for a majority of ℓ -waves, the complex lives long enough to rotate past 0° . While the fit to the experimental high Z data is spoiled, the slope for $Z = 27$ at forward angles is in much better agreement with the data. There is, however, no evidence for any backward peaking; in fact, the yield at backward angles is depleted because of the longer lifetime. Apparently, the lifetime would have to be increased substantially to allow the system to orbit past 0° to backward angles.

The effect of decreasing $\tau(0)$ to 30 is shown in the third column. For all Z 's the side peak has moved to slightly greater angles and become more pronounced with even $Z = 27$ showing a weak bump. A comparison to the data reveals that the overall agreement is poorer than for $\tau(0) = 35$. In the right-most column $\sigma(0)$ has been decreased by 25%. This variation causes the side peak to become narrower and moves it to somewhat smaller

* Unless otherwise stated, units of 10^{-22} sec are used.

angles (compared to $\tau(0) = 35$, $\sigma(0) = 10$). The side peak is also more persistence, as evidenced by the calculations for $Z = 27$ and 41 . The agreement with the data is slightly better near $Z = 36$ but it is worse for atomic numbers removed in Z from the projectile (e.g. $27, 43$). Thus, we feel that the best overall agreement with the data is obtained with $\tau(0) = 35$ and $\sigma(0) = 10$.

4.2 ENERGY DEPENDENCE OF CHARGE AND ANGULAR DISTRIBUTIONS

As is evident from fig. 1 the energy spectra for atomic numbers near the projectile at angles close to the grazing angle are very broad, reflecting a wide range in the degree of energy damping. Since the character of the spectra depends so strongly on Z , there is evidently a strong coupling between the dissipation of energy and the relaxation along the mass asymmetry mode. This point has been made by other authors^{13,25)} but is worth stressing again since the charge and angular distributions depend strongly on energy damping.

In fig. 10 angle-integrated charge distributions are presented for various energy windows. As previously described^{13,14)} these distributions have been constructed by making cuts (20 MeV wide) in the c.m. energy spectra relative to the relaxed energy as defined by the data in fig. 2. The lowest bin in fig. 10 corresponds to the lowest energy. The relaxed peak is centered in bin 7.

The charge distributions exhibit a dramatic dependence on energy bin. For high energy bins they are very narrow and are strongly peaked about the projectile. (Cross sections are not plotted for $Z = 36$ because of serious background problems caused by slit scattering at forward angles.) For the low energy bins, the charge distributions broaden,

but remain centered about $Z = 36$ (see bins 9,10,11). For the lowest energies the distributions are broadest and indicate a shift towards higher Z -values (i.e. $Z > 36$). These observations can be qualitatively understood in terms of the diffusion model. The high energy bins can be associated with high ℓ -waves and, therefore, short lifetimes, which inhibit extensive diffusion and lead to narrow Z distributions. As ℓ -decreases, the lifetime increases, producing broader distributions. For the lowest ℓ -waves the complex lives long enough to exhibit a shift in the centroid, reflecting the driving force toward symmetry. Of course, other factors may contribute to the observed trend. For example, both the overlap δ and the form factor f are expected to increase with decreasing ℓ . In addition, since the available excitation energy is greatest for the lowest ℓ -waves, the greater temperature will tend to broaden the charge distribution.

Rather than plot angular distributions for the various energy bins, we have chosen to construct contour plots after Wilczyński²⁶). A few representative examples are given in fig. 11. In these diagrams contours of constant cross section ($d\sigma/d\theta$) are plotted in the E_T - θ plane in the c.m. system. For atomic numbers well removed from the projectile, the diagrams consist of a single, deep-inelastic ridge that runs roughly parallel to the θ -axis. The contours clearly indicate forward peaking in excess of $1/\sin\theta$. For elements closer to the projectile Z (see $Z = 31$), cross section tends to pile up around 40° . Bulging towards higher energies is clearly apparent in this region. For atomic numbers still closer to the projectile (see $Z = 35, 37$), a second ridge develops. This ridge, which is associated with the

quasi-elastic component, attains its maximum energy at about 50° , and moves rapidly to lower energies as it moves towards smaller angles. The steep slope of this ridge is responsible for the fact that the energy spectra do not show two distinct components. For the reaction $^{107,107}\text{Ag} + 620 \text{ MeV } ^{86}\text{Kr}^{14}$, the slope is smaller, and two components are seen at angles near the grazing. In general it appears that the slope of the high energy ridge decreases with the mass of the target. This observation is supported by the data obtained in studies of ^{86}Kr bombardments of Au and Ag at 620 MeV incident energy and can be better correlated with the ratio $E/B^{18/22}$). As a final point one should note that most of the side peaking near $Z = 36$ is due to the high energy ridge. Indeed, if one makes mental cuts in the contour diagrams of fig. 11, this feature becomes readily apparent.

5. Conclusion

Mass or charge identification is essential for detailed investigations of heavy ion reaction mechanisms. Previous studies of the $^{107,109}\text{Ag} + 620 \text{ MeV } ^{86}\text{Kr}$ and $^{197}\text{Au} + 620 \text{ MeV } ^{86}\text{Kr}$ reactions revealed two distinct regimes of charge distributions and angular distributions. The current investigation of the system $^{181}\text{Ta} + 620 \text{ MeV } ^{86}\text{Kr}$ exhibits intermediate characteristics and demonstrates that the transition between the regimes apparently takes place rather quickly. Even a variation of about 10% in the charge of the target in going from ^{197}Au to ^{181}Ta has a strong effect on the character of the angular distributions. For the slightly heavier $^{197}\text{Au} + ^{86}\text{Kr}$ system, side peaking is observed over a greater range of mass transfer than in the case of $\text{Ta} + \text{Kr}$. On the other hand,

the angular distributions for $^{107,109}\text{Ag} + ^{86}\text{Kr}$ are markedly different from those of the two heavier systems. The dependence of the charge distributions on the mass of the target (at fixed bombarding energy) is quite smooth. The fact that the charge distributions widths tend to be narrow for the heavy systems is consistent with E/B systematics.

The most important conclusions of this work are in connection with the comparison of the diffusion model calculations to the experimental data. The fits to the experimental angular distributions strongly support this approach in interpreting and understanding heavy ion reactions. It should be stressed that the transitional features observed in the Ta + Kr study present a critical test for the model which must systematically reproduce data from a range of systems.

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Figure Captions

Fig. 1 Typical c.m. kinetic energy distributions for several representative atomic numbers detected at four lab angles. "Total" spectra (i.e. all charges) are also shown. The discontinuity in the spectra for 10° is due to the presence of an upper level discriminator used to cut out the elastic peak.

Fig. 2 Mean c.m. energies and FWHM's averaged over the angular range where no quasi-elastic component was visible (see text). The "error bars" correspond to one standard deviation from the mean. The FWHM's were computed from the second moment of the spectra assuming a Gaussian peak shape.

Fig. 3(a),(b) Lab charge distributions observed at various lab angles. Cross sections for $Z = 36$ have been omitted due to uncertainties caused by large background contributions from slit scattering. Statistical errors are shown for the 10° , 25° and 35.5° data when the errors are larger than the data points.

Fig. 4 Center-of-mass angular distributions as a function of atomic number. The curves through the data points guide the eye. Statistical errors are only shown for $Z = 20$ and 25 . The errors are comparable to the size of the data points themselves for higher Z 's.

Fig. 5 Liquid drop potential energy curves for the $^{181}\text{Ta} + ^{86}\text{Kr}$ reaction for various ℓ -waves. The potential energies have been calculated relative to the entrance channel value.

Fig. 6 Diffusion model calculations depicting contours of constant cross section in the plane defined by the charge asymmetry coordinate and the lifetime for different ℓ -values.

Fig. 7 A comparison between the experimental angle-integrated cross section (points) and diffusion model predictions (heavy curve). The experimental values were obtained by integrating between $\theta_{\text{lab}} = 10^\circ - 80^\circ$.

Fig. 8 Absolute comparison between experimental (points) and calculated angular distributions (heavy dashed curves). The thin solid curves through the data points serve only to guide the eye.

Fig. 9 Calculated angular distributions for several values of $\tau(0)$ and $\sigma(0)$ (in units of 10^{-22} sec). The Z-values are given only once at the extreme left of figure.

Fig. 10 Angle-integrated charge distributions for various kinetic energy windows. The bin number multiplied by 20 gives the upper limit of the window in MeV for $Z = 36$. Bin 7 is approximately centered on the relaxed peak.

Fig. 11(a),(b) Contours of constant $(d\sigma/d\theta)$ c.m. in the plane defined by the total c.m. energy and c.m. angle for a few selected Z-values. The spacing of the contours is given by $2^3, 2^4, 2^5, \dots \mu\text{b/rad}\cdot\text{Mev}$.

Fig. 1

Fig. 2

Fig. 3A

XBL 773-691

Fig. 3B

XBL775-3454

Fig. 4

XBL 775-8598

Fig. 5

XBL 775-8600

Fig. 6

Fig. 7

XBL775-3455

Fig. 8

XBL775-3452

Fig. 9

XBL775-3451

Fig. 10

Fig. 11A

Fig. 11B

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