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197au + 620 MeV ^Kr

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Publication Date
1976
Submitted to Physical Review Letters

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January 1976

Prepared for the U. S. Energy Research and Development Administration under Contract W-7405-ENG-48

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DIFFUSIVE PHENOMENA IN THE CHARGE AND ANGULAR DISTRIBUTIONS FOR THE REACTION $^{197}$Au + 620 MeV $^{86}$Kr*

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ABSTRACT

The cross sections and the kinetic energy distributions of fragments with individually resolved atomic numbers have been measured as a function of angle. The variations in the Z distribution widths with angle and the change of the angular distributions from side peaked for Z's close to 36 to forward peaked for Z's far removed from 36 dramatically demonstrates the presence of diffusion along the mass-charge asymmetry coordinate.
Recently both the Z and angular distributions have been measured for the relaxed component associated with the N, Ne and Ar induced reactions. 1-4 While in these experiments the Z distributions are only indicative of incomplete equilibration of the mass/charge asymmetry degree of freedom, the angular distributions as a function of Z clearly indicate a progressive delay for the emission of the particles farther removed in Z from the projectile. This was inferred from the forward peaking of the angular distributions (in excess of 1/sinθ) which progressively disappears for fragments farther removed in Z from the projectile. On the basis of this evidence, 1-5 Moretto and Sventek 6 proposed a diffusion model which quantitatively accounts for the observed features.

In apparent contrast with the above experiments, the reaction products from Kr on heavy targets show a marked side-peaking in the gross angular distribution (all products taken simultaneously) of the quasi-fission peak. 7,8 Furthermore, coarse mass distributions (measured at a few angles) appear to be narrowly peaked around the projectile. 7,8

In order to ascertain whether the differences observed in these two groups of reactions are due to different mechanisms, or alternatively, represent different aspects of the same process, a detailed study of the reaction Au + Kr at 620 MeV bombarding energy was undertaken. As an improvement on previous experiments, a gas ΔE, solid state E telescope, developed by our group, 9 was used which resolved individual atomic numbers up to υ Z = 50. A self-supporting Au foil (0.80 mg/cm²) was bombarded with a 620 MeV Kr beam from the Berkeley SuperHILAC which delivered beam intensities ranging from 10 to 100 charge nA on target. The two independent arms in the scattering chamber each supported two ΔE, E telescopes, separated by 15° or 20°.
The data were analyzed off line on a PDP-9 computer. The data were transformed to the center of mass system by assuming for each Z a mass ratio which minimizes the liquid drop energy of the two touching spheres.

The center of mass kinetic energy distributions were inspected for the presence of an identifiable quasi-elastic component, which would then be subtracted, when possible, from the total spectrum. Close to the grazing angle and for Z's close to the projectile, these two components could not be decomposed and the integration of the relaxed component was omitted.

The data are displayed in three forms:

i) For each Z a contour map of \( \partial^2 \sigma/\partial \Theta \partial \Phi \) is generated in the \( E_T, \Theta_{\text{c.m.}} \) plane; \( E_T \) being the total kinetic energy associated with the exit channel. Examples of these contour plots are given in Fig. 1.

ii) The laboratory cross sections \( d\sigma/d\Omega \) vs Z at various laboratory angles are displayed in Fig. 2.

iii) The center of mass cross sections \( d\sigma/d\Omega \) for each Z are plotted vs center of mass angle in Fig. 3.

In Fig. 1 the quasi-elastic and the relaxed peaks are seen for Z's close to 36. For fragments farther removed in Z from 36, the quasi-elastic peak degenerates into a high energy tail which eventually disappears. At all angles the relaxed peak has an energy fairly close to the calculated Coulomb energies of two spheres. The widths of the kinetic energy distributions are essentially constant both with Z and with angle (\( \sim 50 \) MeV FWHM). For angles close to the grazing angle and for Z's close to 36, one cannot verify the above statements because of the presence of large quasi-elastic peaks.
In Fig. 2 the Z distributions are presented for various laboratory angles. At intermediate angles ($\theta_L = 40^\circ$) the distributions are narrow and sharply peaked about $Z = 36$. The cross section falls off more rapidly in the low $Z$ region than in the high $Z$ region. At more backward angles the distributions are substantially broader, and the cross sections remain constant over a fairly large number of $Z$'s near the peak of the distribution. The centroid appears to be shifted towards higher $Z$'s and the falling off in the high $Z$ region is not very marked. At the most forward angles the distributions are also broader than those observed at intermediate angles, but less broad than those observed at the more backward angles.

The change in the distributions from narrow to broad can be interpreted as due to the diffusion along the mass asymmetry coordinate of the "intermediate complex".\textsuperscript{5,6} It appears that the narrow distributions are relatively "young" and should be associated with short interaction times, because diffusion has not had time to randomly exchange many particles. On the same basis, broader distributions can be considered older and associated with longer interaction times. Similarly the shift or drift of the centroid toward higher $Z$'s is the result of a diffusion process governed by the potential energy of the intermediate complex which favors the exchange of particles in the direction of symmetry. Again the drift is more visible in the broader or older distributions.

A somewhat puzzling feature is observed in the relationship between the "age" of a distribution in $Z$ and the angular range at which it is observed. In fact, one notices a peculiar inversion: "old" distributions are observed at the broader angles, young distributions at intermediate angles, and "middle-aged" distributions at forward angles.
If one assumes that the lifetime of the intermediate complex decreases rapidly with increasing impact parameter, the above feature can be qualitatively understood as an impact parameter effect. The distributions observed at the larger angles appear to be associated with small impact parameters or near head-on collisions. Although the intermediate complex lives the longest, the angular velocity is so small that the decay products do not reach too far forward. For the intermediate impact parameters the collision angle is larger, the intermediate complex rotates faster and the lifetimes are not too short, so that the products reach very forward angles. Finally, at the largest impact parameters, although the collision occurs quite peripherally, thus forming rapidly rotating "complexes", the decay occurs so quickly that the fragments actually are emitted at angles not quite as forward as are those associated with intermediate impact parameters.

Figure 3 shows the center of mass angular distributions for the various Z's. These angular distributions are side peaked (~ 40°) for Z's close to the projectile. As one moves away from Z = 36, towards both lower and higher Z's, the small angle cross section increases with respect to the peak of the angular distribution. Therefore the side peaking evolves first into a shoulder and then disappears entirely, leaving angular distributions which are generally forward peaked and similar to those observed in Ne and Ar induced reactions (see also Fig. 1).

Also these features can be qualitatively explained in terms of a diffusion model. For Z ~ 36 the decay time is so short that no fragment reaches 0° thus resulting in a side peaking. Fragments with Z progressively larger or smaller than 36 are populated by diffusion on a progressively
longer time scale. This results in a selection of progressively larger lifetimes. The complex can then rotate more forward and actually some fragments begin being emitted close or even beyond 0°, giving rise to the transformation of the side peak into a shoulder. At very large distances in Z from the projectile, the lifetimes become so long that the complex succeeds in rotating past 0°. This partial orbiting is sufficient to generate a sharply forward-peaked angular distribution.

In conclusion, it appears that in the same experiment a natural and continuous connection is seen between the side-peaked angular distributions and the forward-peaked angular distributions, typical of the reactions with lighter ions.

This evidence, on one hand supports the general predictions of the diffusion model, and on the other, it offers the possibility of studying diffusion times and decay times as a function of the impact parameter.
FOOTNOTES AND REFERENCES

*This work done under the auspices of the U. S. Energy Research and Development Administration.

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FIGURE CAPTIONS

Fig. 1. Contour plots of $\frac{\partial^2 \sigma}{\partial E \partial \theta}$ in the $E_{c.m.}, \theta_{c.m.}$ plane for various atomic numbers.

Fig. 2. Laboratory $Z$ distributions ($d\sigma/d\Omega$) for various laboratory angles.

Fig. 3. Center of mass angular distributions for various atomic numbers.
620 MeV $^{86}$Kr + $^{197}$Au

Fig. 1
$620 \text{ MeV } ^{86}\text{Kr} + ^{197}\text{Au}$

$x =$ Uncertain decomposition from quasi-elastic

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$d\sigma/d\Omega (\mu b/sr)$

$Z$

Fig. 2
Fig. 3
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