Energy Dependence of Deeply Inelastic Scattering of ^{84}Kr from ^{208}Pb†

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The angular distribution for deeply inelastic scattering of ^{84}Kr from ^{208}Pb at laboratory energies of 494, 510, and 718 MeV exhibits a strong peak that moves forward and sharpens with increasing energy. Forward peaking never becomes prominent. The integrated cross section is nearly equal to the total absorption cross section at all energies. These results are inconsistent with a unique critical radius for fusion and are in contrast to those for systems with lower Z_1Z_2 product.

Recent investigations[1-5] of nuclear reactions induced by massive ($A \geq 40$) projectiles have revealed two features that are strikingly different from those exhibited by light-particle interactions. The first is the relatively small fraction of the total reaction cross section that goes into reactions associated with the complete fusion of the target and projectile nuclei.[3] The majority of the cross section appears in reaction channels that exhibit angular distributions peaked near the grazing angle,[1-4] indicative of a relatively fast, direct process. The second unusual feature is the large kinetic energy loss associated with these direct reactions. This energy loss is exceptionally large for a direct reaction, hence the process is often referred to as "deeply inelastic" scattering. The distribution in total kinetic energy in the exit channel extends well below that calculated for Coulomb repulsion between two spherical products, suggesting nuclear distortion of the reaction products.[3] For this reason the process is sometimes designated "quasifission."

Previously reported studies of this process with very heavy projectiles have been limited to energies fairly close to the Coulomb barrier. We have therefore studied this process up to the highest bombarding energy presently available. Of particular interest to us was whether the deeper interpenetration of the ions at the higher bombarding energy would result in fusion. Our results indicate that fusion remains improbable even at the highest available energies, in contradiction to the predictions based on studies of lighter nuclei. In particular, we find that even though there is sufficient energy for the nuclei to interpenetrate well within the critical radius for fusion proposed by Galin *et al.*,[6] relatively little fusion takes place.

It has been proposed by Wilczynski[7] that the partners in such collisions should orbit around one another; the corresponding angular distribution should be forward peaked. Our angular distributions are peaked near the grazing angle and show no evidence for significant forward peaking. Such orbiting appears, therefore, to be of minor importance in these reactions.

The experiments were performed using krypton beams from the Lawrence Berkeley Laboratory Super-HILAC. Energy spectra were obtained using surface-barrier solid-state detectors that subtended a solid angle of 1.4 msr. The elastic peak typically had a full width at half-maximum of 8–10 MeV, primarily due to the energy dispersion of the beam.

At most angles the energy spectra exhibit a well-defined peak corresponding to the deeply inelastic events. As one approaches the grazing angle from either more forward or more backward angles the valley between the elastic and deeply inelastic events disappears. At the lower bombarding energies this disappearance is apparently due to a filling of the valley, whereas at the higher bombarding energy the deeply inelastic peak gradually moves up in energy and merges with the quasielastic events at the grazing angle. This behavior suggests that for the grazing trajectories at the higher bombarding energy the processes responsible for the energy dissipation are not able to damp completely the incident kinetic energy.

The angular distributions obtained in this work at $E_{\rm lab} = 494$, 510, and 718 MeV are presented in Fig. 1 along with that obtained at 600 MeV by

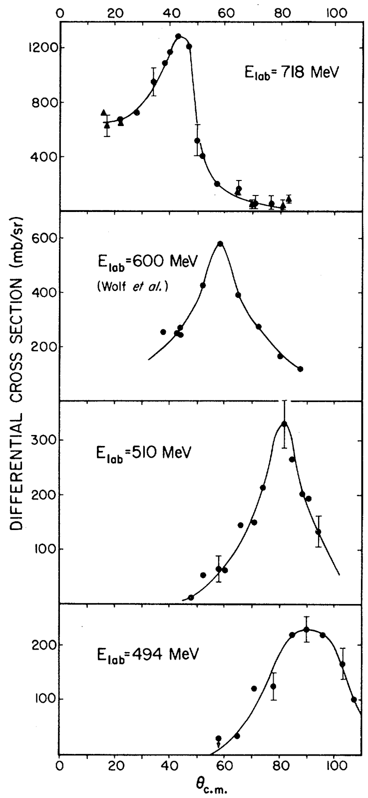

FIG. 1. Deeply inelastic angular distributions for ^{84}Kr and ^{208}Pb. Included are the $^{84}Kr + ^{209}Bi$ data of Wolf *et al.* (Ref. 4).

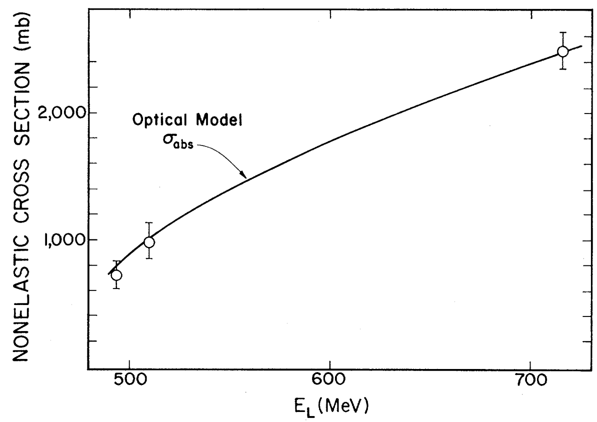

FIG. 2. Angle-integrated cross sections for the sum of the deeply inelastic and quasielastic scattering of $^{84}Kr + ^{208}Pb$ as a function of energy. The solid line is an optical-model prediction of the total absorption cross section.

Wolf *et al.*[4] At angles very near the grazing angle it was not possible to separate unambiguously the deeply inelastic from the quasielastic events. Thus in our work we have included both of these processes in constructing the angular distributions.

The maximum in the angular distribution is, in each case, slightly forward of the angle at which the elastic-scattering cross section has fallen to $\frac{1}{4}$ of that for Rutherford scattering. The peaks in the angular distribution move forward and become sharper as the bombarding energy is increased. Both of these features can be understood in terms of the influence of the attractive nuclear potential. The deeply inelastic scattering arises from lower partial waves than does the elastic scattering and hence is more strongly influenced by the nuclear potential. The sharpening of the peak with increasing energy can be attributed to a focusing effect whereby low partial waves, which experience the greatest Coulomb repulsion and lead to large-angle scattering at low energy, at higher energies penetrate sufficiently into the region of the attractive potential to be bent forward toward the same angles as higher partial waves experiencing both less Coulomb and less nuclear deflection. A more quantitative account of these features in terms of deflection functions generated from an optical-model potential will be presented elsewhere.[8] It is interesting to note, however, that at the highest bombarding energy the angular distribution has flattened out at the smallest angles for which measurements have been made. It is possible that at still smaller angles the cross section may rise again due to orbiting as suggested by Wilczynski[7] in the interpretation of reactions in the $^{40}Ar + ^{232}Th$ system. However, since the contribution from orbiting can be only a small fraction of the integrated deeply inelastic scattering for the angular range observed, and since this cross section accounts for almost all of the available total reaction cross section (as discussed below), orbiting cannot play a major role in the $^{84}Kr + ^{208}Pb$ system at the energies studied. This difference from the $^{40}Ar + ^{232}Th$ system probably originates from the fact that the charge product and hence the Coulomb deflection is larger in the $^{84}Kr + ^{208}Pb$ system. At bombarding energies higher than those presently available it may be that an increase in cross section at forward angles will appear.

The angle-integrated cross sections for the sum of the deeply inelastic and quasielastic scattering are plotted in Fig. 2 as a function of the laboratory energy. Also included in this figure is the prediction of the total absorption cross section calculated from the optical model with parameters that gave a fit to the elastic-scattering data.[9] As is evident, the sum of the deeply inelastic and quasielastic yields accounts for virtually all of the calculated cross section. The deeply inelastic yield is the predominant contributor to this sum. At 500 MeV no direct evidence exists for compound-nuclear processes although an upper limit of 40 mb for the fusion process has been estimated.[1] In a thick-target experiment with 605-MeV Kr ions on ^{238}U, Kratz, Morris, and Seaborg[5] report a fusion-fission yield of 55 mb out of a total reaction cross section of 1265 mb. At 718 MeV we estimate an upper limit to the fusion cross section of approximately 800 mb. This estimate was made by assuming that the large-angle tail seen in the 718-MeV deeply inelastic angular distribution is due to a $1/\sin\theta$-type angular distribution resulting from fusion-fission events. At 718 MeV any symmetric-mass primary fission fragments resulting from the amalgamation of ^{84}Kr with ^{208}Pb have kinetic energies very similar to the deeply inelastic events and hence are not separable in the energy spectra.

At bombarding energies near 500 MeV the large preponderance of the deeply inelastic process relative to complete fusion is not as surprising as it might at first appear. The strong Coulomb deflection keeps the target and projectile so far apart, even for the lowest partial waves, that amalgamation and fusion are unlikely. Although impact parameters between 0 and 5.2 fm contribute to the nonelastic cross section, this range of impact parameters collapses to a smaller range of distances of closest approach, 12 to 14 fm. Thus at the lower bombarding energies all of the nonelastic processes can be thought of as surface reactions. At the highest bombarding energy this is no longer the case. The distance of closest approach becomes much smaller and the bulk of the nonelastic cross section can no longer be expected to be surface reactions; some restriction other than the surface nature of the collisions must be important in preventing fusion at the higher energies.

Galin *et al.*[6] have examined the systematics of fusion cross sections (as distinguished from total reaction cross sections) for a variety of heavy-ion systems. They have found that all of the data available at the time of their investigation were consistent with the concept of a critical distance of closest approach, R_{cr}, which must be reached in order for fusion to occur. They have included the effects of the nuclear potential on the trajectory, obtaining a value of $R_{cr} = (1.0 \pm 0.07)(A_1^{1/3} + A_2^{1/3})$ for the particular potential employed. This criterion, which gives $R_{cr} = 10.3$ fm for this case, is qualitatively consistent with the small upper limit to the fusion cross section at 500 MeV. At the higher bombarding energy of 718 MeV one expects 1200 ± 200 mb at 718 MeV by this criterion. This is one and one half times as large as the upper limit we have deduced for a possible fusion-fission contribution to the nonelastic yields, and much larger than the difference between the calculated absorption cross section and the integrated nonelastic cross section. Thus at this higher energy one expects, on the basis of the smaller distances of closest approach and the systematics for other systems, a larger fusion-fission cross section than is observed, suggesting that some other criterion is not being satisfied.

The absence of a sizable fusion-fission component may be due either to entrance channel effects or to the properties of the compound system if formed. The liquid-drop-model fission barrier for this high-Z^2/A compound nucleus is essentially zero. Shell effects may produce a barrier of a few MeV, but at the excitation energies involved the shell effects are expected to be dissolved so that there is not an effective barrier. Angular momentum effects would also result in a vanishing fission barrier for most partial waves. It is more likely that the absence of fusion-fission events is due to entrance-channel effects. Even if there were a barrier to fission, trajectory calculations of Sierk and Nix[10] suggest that few, if any, of the trajectories would bring the centers of mass as close together as would be required to be inside the fission saddle.

Since this Letter was originally submitted, Tamain and co-workers[11] have reported on the variation of the energy spectrum and angular distribution with bombarding energy for Cu plus Au. Their results for the energy spectra are in accord with our low-energy results—the deeply inelastic events are fully damped at all energies, and near the grazing angle the valley between the deeply inelastic and elastic peaks tends to fill in with quasielastic events. At higher energies, however, our results indicate that the deeply inelastic events are not fully damped near the grazing angle. Furthermore, their angular distributions are forward-peaked indicating orbiting, suggesting that this pehnomenon is strongly dependent on the Z_1Z_2 product of the target and projectile.

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Inelastic Collision Induced by Intense Optical Radiation*

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A large cross section for inelastic collision is induced by an incident laser tuned to the frequency of the interatomic energy defect. We study energy transfer from the Sr $5p\,^1P^\circ$ level to the Ca $4d\,^1D$ level and measure a cross section for inelastic collision of 3×10^{-16} cm^2 at a laser power density of 8.6×10^6 W/cm^2 and a wavelength of 6409.0 Å.

The cross section for inelastic collision between atoms is infinitesimally small if the energy defect ΔE is large with respect to kT. In this Letter we report the first observation of a process where a large cross section for inelastic collision is created by applying optical radiation at a frequency $\hbar\omega=\Delta E$. Energy transfer is initiated or "switched" by the presence of the optical radiation. Inelastic collision processes of this type have recently been predicted by Gudzenko and Yakovlenko[1] and by Harris and Lidow.[2]

We have observed this process in the system (Fig. 1)

$$\mathrm{Sr}(5p\,^1P^\circ)+\mathrm{Ca}(4s^2\,^1S)+\hbar\omega(6409\text{ Å}) = \mathrm{Sr}(5s^2\,^1S)+\mathrm{Ca}(4d\,^1D). \quad (1)$$

Energy was first stored in the radiatively trapped $5p\,^1P^\circ$ level of Sr I. This level was populated by two-photon pumping of the $5d\,^1D$ Sr level, followed by radiative decay. Inelastic collision to the $4d\,^1D$ level of Ca I was effected by a second laser beam at 6409 Å.

During collision of an excited Sr $5p\,^1P^\circ$ atom and a ground-state Ca $4s^2\,^1S$ atom the strong dipole-dipole coupling of the $5p$-$5s$ Sr transition and the $4p$-$4s$ Ca transition causes a virtual transition of the Ca atom. Absorption of a 6409-Å

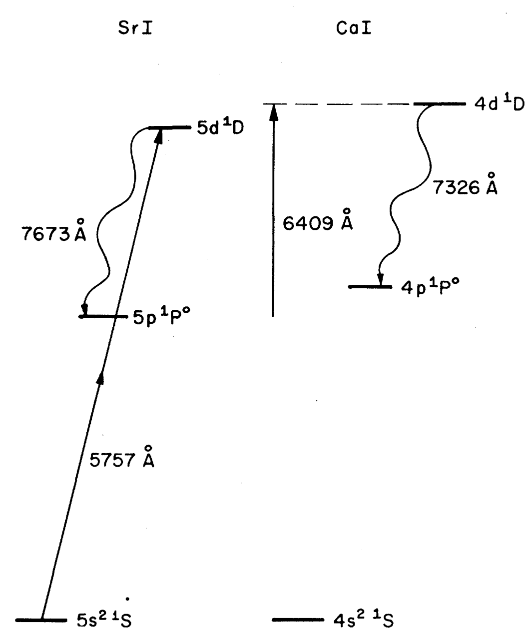

FIG. 1. Energy level diagram for Sr-Ca induced-collision experiment.