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ANGULAR MOMENTUM TRANSFER IN DEEP INELASTIC PROCESSES

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ABSTRACT

Gamma-ray multiplicities have been measured as a function of fragment Z both for the relaxed and quasi-elastic component in the reaction of 175 MeV ^{20}Ne on ^{nat}Ag. Evidence for maximum transfer of orbital angular momentum to rotation of the fragments is seen at 90° for the relaxed component, indicating a rigid rotation of the intermediate complex. Possible evidence for angular-momentum transfer via mass transfer and other mechanisms are discussed for the quasi-elastic component.

Extensive studies of heavy-ion reactions have shown the existence of an "intermediate complex" consisting of two well-defined fragments in contact, undergoing equilibration.[1,2] The most important relaxation processes appear to be transfer of the kinetic energy of relative motion to the internal degrees of freedom and mass transfer between the two fragments. The time constants of these relaxation processes differ. They have been determined to various degrees of accuracy from the study of the fragment angular distributions. In particular, the diffusion constant associated with the slowest mode, the mass-asymmetry degree of freedom, is now known with reasonable accuracy.[2]

One aspect of these reactions which has received only minor attention as yet, is the transfer of entrance channel orbital angular momentum into rotation of the two fragments constituting the complex.[3-5] If mass transfer is absent, the angular-momentum transfer, induced by frictional forces acting between the two fragments, can be envisaged to pass through several stages.[6,7] In the initial stage the two nuclei slide on each other. The viscous forces caused by sliding exert a torque on each fragment which sets them into rotation until the peripheral velocities are matched and the system reaches the "rolling" stage. Finally rolling friction slows down the rolling until the fragments rotate rigidly in a "sticking" configuration. At the onset of sliding, the moment of inertia characterizing the system is μR^2 where μ is the reduced mass and R the distance between the centers of the two fragments. For the sticking configuration, the relevant moment of inertia becomes $\mu R^2 + J_1 + J_2$, where J_1 and J_2 are the moments of inertia of the fragments. The picture becomes more complicated when mass transfer between target and projectile is considered, since angular momentum is transferred with the mass. It is not clear as yet which of the two mechanisms may dominate in general, though there are indications that either one may do so under appropriate circumstances.

The system studied was the intermediate complex formed in the reaction of 175 MeV Ne with ^{nat}Ag.[8] To determine the total spin of the fragments in a particular exit channel, we measured the γ-multiplicity of the reaction. The simultaneous determination of the fragment charges and their angular distribution makes it possible to assign the dynamical state of the system according to the picture discussed above.

The deexcitation γ-radiation was observed in two 3x3" NaI detectors at 75 and 105° relative to the beam direction and 60 cm from the target. The γ-rays were recorded in coincidence with one fragment from the intermediate complex, which was detected in either of two telescopes consisting of a solid state E and gas ΔE counter.[9] This coincidence requirement allowed us to measure the γ-multiplicity for individual atomic numbers Z and different kinetic energy windows. Neutrons were discriminated against by their longer time-of-flight. Scaled-down singles were recorded simultaneously. The measurements were performed at telescope angles of 25° (the grazing angle), 35° and 90° with respect to the beam direction.

The Z identification was performed on ΔE-E maps as described elsewhere,[10] and kinetic-energy distributions were obtained for each atomic number. To obtain γ-multiplicities, the coincident γ-spectra were corrected for random events (~ 10%) and then unfolded using a carefully adjusted response function and the absolute efficiency of the NaI-detectors. When normalized to the number of singles events in the gating Z and kinetic-energy region, the unfolded γ-spectra can be integrated to give the average γ-multiplicities.

The fragment-kinetic energy spectra, in the vicinity of the grazing angle and for fragments close in Z to the projectile, exhibit two peaks. The higher energy peak is called "quasi-elastic" and the lower energy peak is called "relaxed" or "deep-inelastic". As one moves towards atomic numbers farther removed from the projectile, the quasi-elastic peak moves down in energy and eventually merges with the relaxed peak. Since there is no clear distinction between quasi-elastic or deep-inelastic processes, these names merely designate earlier or later stages of the equilibration of the intermediate complex. At large angles only the relaxed component shows in the kinetic-energy spectra for all atomic numbers. Figure 1 illustrates the various kinds of kinetic-energy spectra. At 25° and 35°, and for atomic numbers ranging from 5 to 12, two energy windows, corresponding to the quasi-elastic and the relaxed component, were investigated. At Z = 10 a third window including the "elastic" peak was used. At 90° only the relaxed component was present.

In Fig. 2 the γ-multiplicity M_γ is shown as a function of Z for the relaxed component at the three lab angles. In Fig. 3, M_γ is given for the quasi-elastic component as well as for the Z = 10 elastic component. The error bars refer only to statistical errors. For comparison calculated γ-multiplicities for the limiting cases of rolling (dashed lines) and sticking (solid lines) are plotted for two values of the entrance-channel orbital angular momentum (50 ħ and 70 ħ), assuming two sharp spheres in contact [$R = 1.225\ (A_1^{1/3} + A_2^{1/3})$ fm]. The intrinsic angular momentum is taken as twice the γ-multiplicity.

The value of 70 ħ for the entrance channel is in fair agreement with the value to be expected from the sum of the known evaporation residue cross section of 900 ± 200 mb[11] (corresponding to an upper angular momentum cut-off $\ell_{ER} = 57 \pm 7$), and the deep-inelastic cross section of 400 mb, bringing the upper angular momentum cut-off close to $\ell = 70$.

In the rolling case the intrinsic spin is 2/7 of the total angular momentum independent of the mass asymmetry,[6] whereas in the sticking case the intrinsic spin is 2/7 of the total only for a symmetric fragmentation, but increases towards a value equal to the total angular momentum as the asymmetry approaches the limiting configuration of a compound nucleus ($Z \rightarrow 0$).

Comparing the data with the calculated lines, one sees that at 90° the fairly rapid increase of M_γ with decreasing Z suggests that the limit of rigid rotation is approached. At 90° the fragments are most likely to have orbited through 0°, consequently the decay times are quite long and probably sufficient to lead the system to the sticking limit. The 70 ħ line for sticking agrees best at high Z's, while the 50 ħ line agrees best for the lowest Z's. Two possible causes may be responsible for this feature: a) the lower Z's have not yet reached the sticking limit; b) the low Z's are produced selectively by lower ℓ-waves. The second hypothesis is supported by the diffusion model[2,8] in which the driving force for this reaction is directed towards lower Z's for the lower ℓ-waves and towards symmetry for the higher ℓ-waves.

The substantially lower multiplicities observed for the lower Z values at 25° and 35° could be due to a very strong preference of these Z's for lower ℓ-waves, but this behavior can be better understood in terms of incomplete angular momentum transfer. The lowest multiplicities are observed at the grazing angle 25° and may be thought to contain the shortest decay times. That is, the fragments may be rolling on each other, but have not had the time to progress to the sticking stage. However, the agreement of the 25° and 35° data with the rolling value should not necessarily be taken as good evidence for the existence of a rolling stage, since little is known about the characteristic times for rolling and sliding friction , and since the system must pass through the 2/7 value in going from sliding to sticking.

For the quasi-elastic data of Fig. 3, as one moves away from the Z of the projectile, the M_γ rise very rapidly from extremely low values to around the "rolling" limit. It is tempting to relate such a rapid increase in M_γ with the corresponding rapid decrease in kinetic energy of the quasi-elastic peak as one moves from Z = 10 towards lower Z's. The dependence of both kinetic energies and γ-multiplicities seems to be consistent with that predicted by a direct mass transfer (dashed line in Fig. 3).[4] It is possible that other mechanisms are in effect,especially close to Z = 10, where the "direct" mechanism would give smaller γ-multiplicities and larger kinetic energies than observed.

In conclusion, it can be said that the data presented here furnish strong evidence that the intermediate complex approaches rigid rotation in a time comparable to the rotational period of the complex. The evidence from the low Z quasi-elastic component is consistent with the suggestion that the fastest transfer of angular momentum is accomplished by direct mass transfer.

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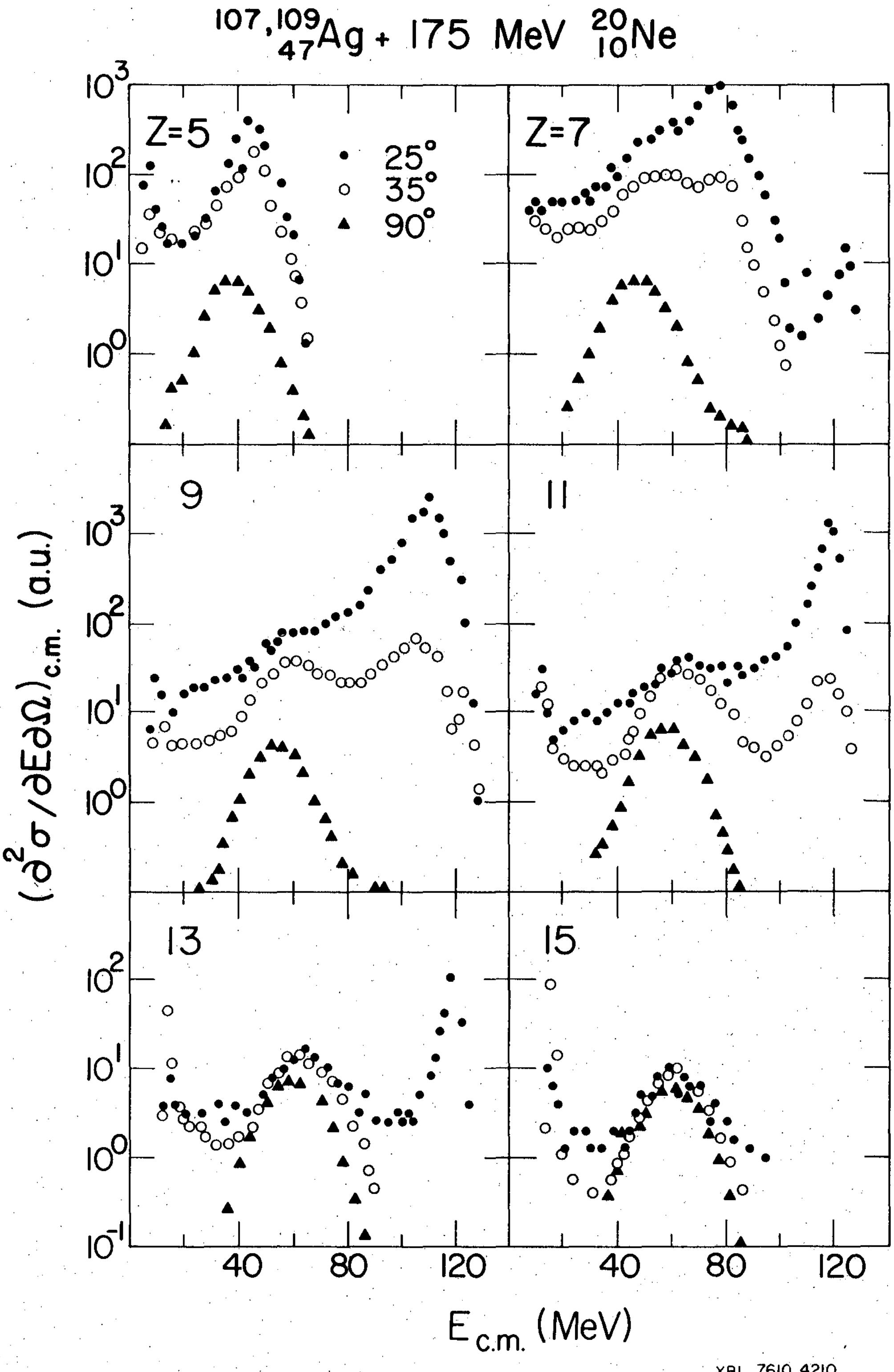
FIGURE CAPTIONS

Fig. 1: CM kinetic energy spectra (singles) for various atomic numbers of the fragment.

Fig. 2: Gamma-multiplicity vs. Z for the relaxed component.

Fig. 3: Gamma-multiplicity vs. Z for the quasi-elastic component.



$^{107,109}_{47}Ag + 175 MeV ^{20}_{10}Ne$
Z=5
Z=7
9
11
13
15
• 25°
○ 35°
▲ 90°
$(\partial^2\sigma/\partial E\partial\Omega)_{c.m.}$ (a.u.)
$E_{c.m.}$ (MeV)
40
80
120
XBL 7610 4210

Fig. 1

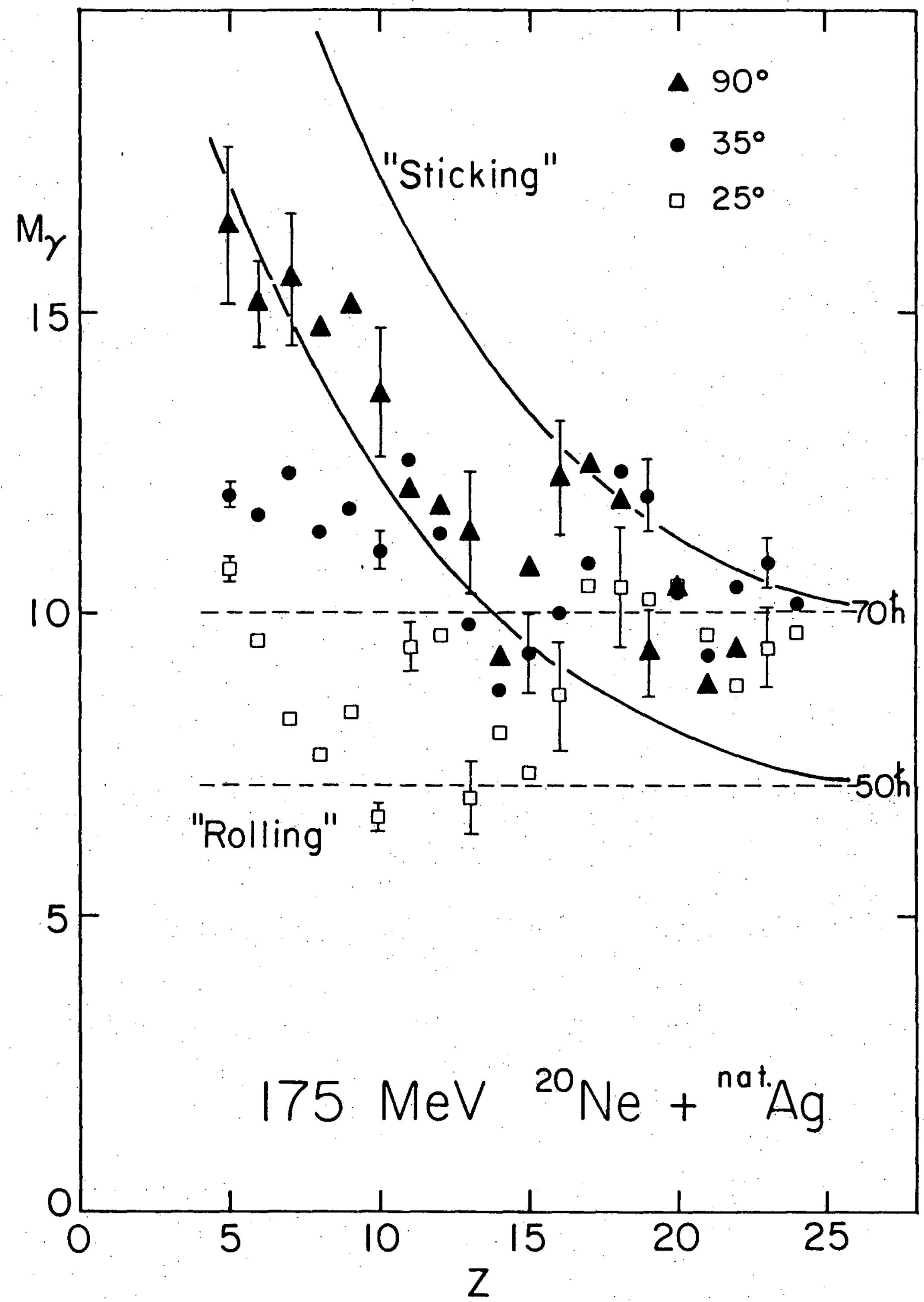


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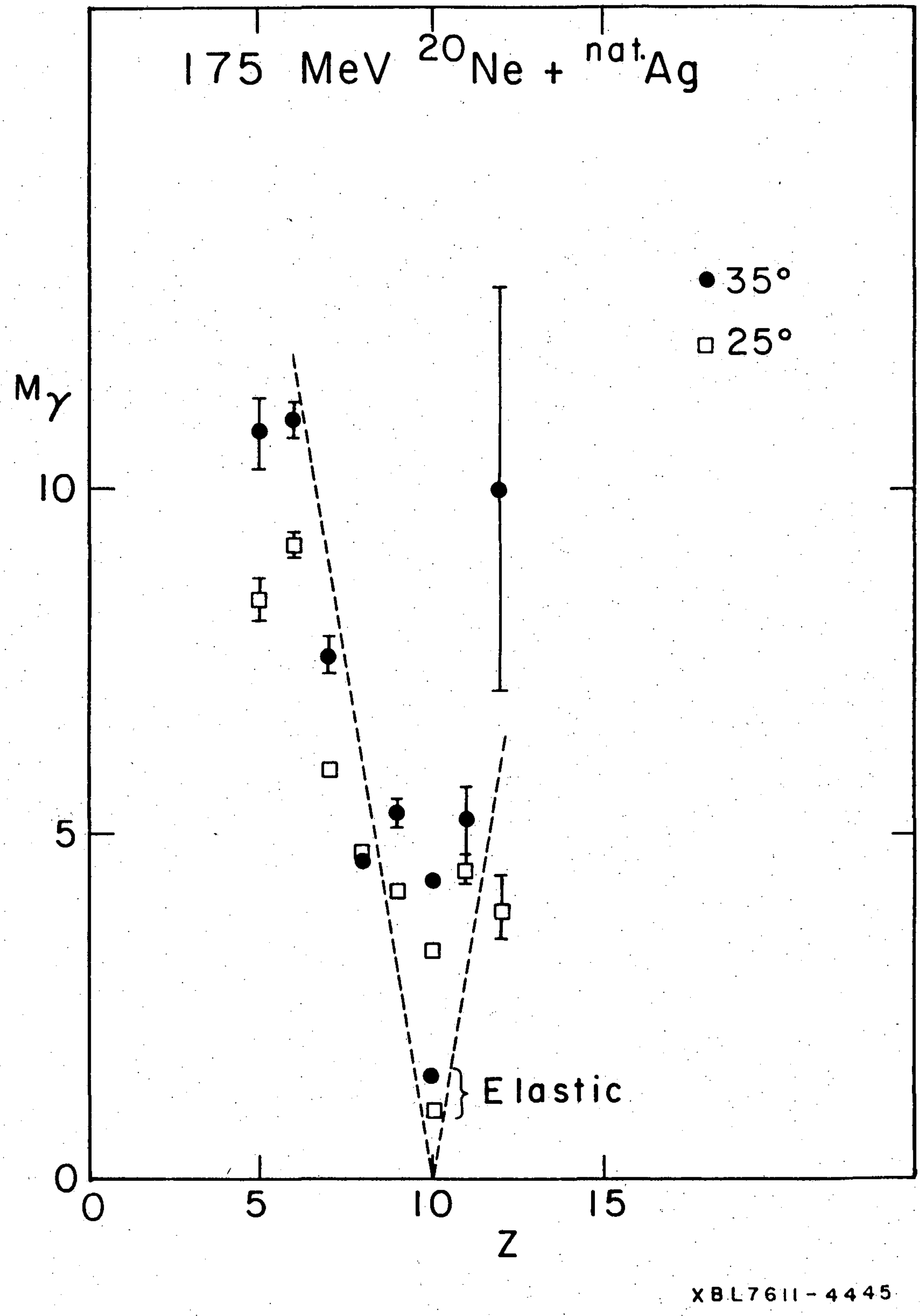
Fig. 2



175 MeV ^{20}Ne + $^{nat.}$Ag
35°
25°
M_γ
10
5
0
0
5
10
15
Z
Elastic
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Fig. 3

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