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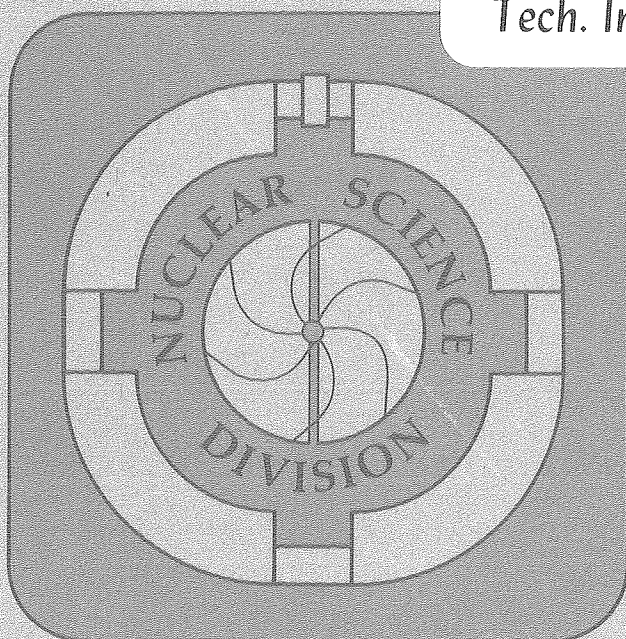
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THE DEEP INELASTIC REACTION: 664 MeV $^{84}\text{Kr} + \text{natAg}$

L.G. Sobotka, C.C. Hsu, G.J. Wozniak, G.U. Rattazzi,
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EVIDENCE FOR RIGID ROTATION AND LARGE DEFORMATIONS
IN THE DEEP INELASTIC REACTION:
 $664 \text{ MeV } ^{84}\text{Kr} + \text{natAg}$

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Abstract

Out-of-plane angular distributions have been measured for sequential alpha decay from target-like fragments produced in fully damped heavy-ion collisions. Fragment spins were extracted from the angular distributions as a function of mass asymmetry. These spins are in agreement with those obtained from a simultaneous gamma-ray multiplicity measurement. Both the fragment kinetic energies and intrinsic spins are consistent with rigid rotation of an intermediate complex consisting of two substantially deformed spheroids.

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A prominent feature of deep-inelastic reactions is the conversion of orbital angular momentum into intrinsic spin of the two product nuclei. This process has been studied by determining either the sum of the spins of the two fragments or the spin of an individual fragment. The sum of the spins is commonly derived from gamma-multiplicity data¹, M_γ , while individual spins are most frequently extracted from the angular distributions of sequential fission fragments.¹⁻³ The simultaneous determination of both types of information would provide a powerful cross check of the two methods and would allow one to study the partitioning of angular momentum within the di-nuclear complex. Unfortunately, because the fission process converts a substantial amount of the intrinsic spin of the fissioning fragment into orbital angular momentum, it is not compatible with the M_γ technique. A compatible alternative is the measurement of the out-of-plane distribution of sequentially evaporated light particles.⁴ Recently, R. Babinet et al.⁵, have shown that by proper selection of the reaction system and detection angles one can extract the spin of an individual fragment from its associated out-of-plane distribution of light particles.

In this letter we report for the first time an investigation of the transfer and partitioning of the angular momentum via simultaneous measurements of both the out-of-plane angular distribution of evaporated α -particles and the continuum γ -ray multiplicity. Individual fragment spins were extracted from the α -particle data utilizing a statistical mechanical formalism^{6,7} which explicitly includes fragment spin misalignment⁸ and neutron/alpha particle competition. The two spin

determinations agree and a consistent picture concerning the partitioning of angular momentum is achieved.

A schematic diagram of the reaction kinematics and of the experimental configuration is shown in Fig. 1. A 664 MeV ^{84}Kr beam, extracted from the Lawrence Berkeley Laboratory SuperHILAC, impinged upon a $586\text{ }\mu\text{g}/\text{cm}^2\text{ }^{nat}\text{Ag}$ target. A ΔE -E (11 μm -300 μm) solid state telescope ($d\Omega = 6.8\text{ msr}$) was placed slightly behind the grazing angle to detect the Kr-like fragment and to define the reaction plane. On the opposite side of the beam, an arc containing four solid state α -particle telescopes (40 μm - 5 mm) was positioned so that its in-plane projection approximately coincided with the direction of the target-like fragment. Absorbers ($10.1\text{ mg}/\text{cm}^2\text{ Ta}$) were placed in front of the α -particle telescopes to reduce the rates of heavy ions, x-rays, and electrons striking these counters. To measure M_γ an array of seven $7.6 \times 7.6\text{ cm}$ NaI detectors was positioned above the reaction plane at an out-of-plane angle of 45° and 8" from the target. This distance was sufficient to separate neutrons from γ -rays by their time-of-flight.

Utilizing two body kinematics, the $Z - \alpha$ coincidence events were reconstructed and transferred event-by-event into the rest frame of the undetected Ag-like emitter. The resulting α -energy spectra were consistent with evaporation from the Ag-like recoils. In addition a weak lower energy component in the transformed spectra due to emission from Kr-like fragments was observed. This contribution contaminated the main component by less than 7%.

In the mass region covered by the present study, the γ -ray multiplicity is proportional to the sum of the fragment spins.^{9,10} Thus requiring an increasing number of γ -rays to be in coincidence with the Z - α events, should bias the fragments' spin distribution towards larger values and result in a greater focusing of the angular distributions into the reaction plane. The energy integrated out-of-plane α -distributions in the rest frame of the emitter are shown in Fig. 2. As expected the angular distributions associated with the high γ -ray multiplicity events (Fig. 2b) display a larger anisotropy than those without the gamma-ray requirement (Fig. 2a). These anisotropies, quantitatively expressed by the in- to out-of-plane ratios, indicate that the α -particle distributions are sensitive to the spin of the emitting nucleus. Furthermore, the anisotropy increases as the size of the emitter increases indicating that the fragment's spin increases with the mass asymmetry of the exit channel.

To quantitatively extract the fragment's spin from the out-of-plane distributions, we have utilized the formalism of Moretto et al.^{6,7} In this statistical model the spin alignment of each of the deep-inelastic fragments is described by gaussian distributions in the Cartesian coordinates of the angular momentum with widths σ_x , σ_y , and σ_z . It has been shown that the light particle decay width is given by:¹¹

$$\Gamma \propto \frac{1}{S(\theta, \phi)} \exp \left(\frac{-I_z^2 \cos^2 \theta}{2S^2(\theta, \phi)} \right), \quad (1)$$

where $S^2(\theta, \phi) = K_0^2 + \sigma_x^2 \cos^2 \phi \sin^2 \theta + \sigma_y^2 \sin^2 \phi \sin^2 \theta + \sigma_z^2 \cos^2 \theta$.

Here K_0 is the root-mean-square projection of the angular momentum on the fragment-alpha separation axis.

Assuming that the bulk of the total decay width is due to neutron emission, integration over the fragment's spin distribution, of the form $(2\ell + 1)$ and bound by $I_{\min}$ and $I_{\max}$, leads to the following expression for the angular distribution

$$W(\theta, \phi) \propto [\exp(-I_{\min}^2 A) - \exp(-I_{\max}^2 A)] / SA \quad (2)$$

where $A = (\cos^2 \theta / 2S^2 - \beta)$ and $\beta = (\hbar^2 / 2T)(1/J_n - 1/J_\perp)$. In this expression the competition between neutrons and alphas as a function of angular momentum is accounted for through the parameter β . The moment of inertia J_n is that of the emitting nucleus after neutron emission, while $J_\perp$ is the moment of inertia perpendicular to the separation axis at the critical shape for the alpha particle decay.

If one makes the simplifying assumption that $\sigma_x = \sigma_y = \sigma_z \equiv \sigma$, then $S^2 = K_0^2 + \sigma^2$. The parameter K_0^2 can be expressed in terms of the temperature T and the moments of inertia parallel ($J_\parallel$) and perpendicular ($J_\perp$) to the separation axis, $K_0^2 = (T/\hbar^2)(1/J_\parallel - 1/J_\perp)^{-1}$. These two moments of inertia were calculated using the equilibrium configuration of the rotating fragment-alpha complex in a spheroid-sphere model. Values of σ^2 were calculated using the model of Ref. 8. To estimate $I_{\min}$ the experimental evaporation residue cross section¹² and rigid rotation of the deformed deep-inelastic complex were used. The experimental

out-of-plane distributions were then fit to equation 2 by adjusting $I_{\max}$. In general these fits reproduce the data quite well and are shown as solid lines in Fig. 2.

The deformation of the deep-inelastic complex used to calculate $I_{\min}$ was estimated from the measured fragment kinetic energies. For two equally deformed spheroids with no neck the fragment energies are given by

$$E_L = \frac{M_H}{M_L + M_H} \left(\frac{Z_L Z_H}{d} F + \frac{\ell_{\text{rel}}^2 \hbar^2}{2\mu d^2} \right) \quad (3)$$

Here, the Coulomb correction factor (F), the distance between centers (d), and the relative angular momentum (ℓ_{rel}) are deformation dependent. In Fig. 3a the experimental fragment energies (plus signs) are compared to calculated values (curves) using Eq. 3 for several deformations. For this model a ratio of axes C/A of about two is needed to reproduce the data.

In Fig. 3b are plotted the rms spin values of the large fragment (I_H) extracted from the fitted distributions shown in Fig. 2. The observed increase in spin with increasing asymmetry is clear evidence of rigid rotation. A comparison of the data to the calculations again indicates that large deformations are needed to correctly reproduce the

magnitude of I_H . The extracted spin values are quite insensitive to I_{min} and the error bars shown in Fig. 2b were estimated by varying the nuclear temperature (on which both β and S depend, see Ref. 6) over a range consistent with the α -particle spectra.

In Fig. 3c the sum of the spins of both fragments as determined by two independent methods are compared to rigid-rotation calculations. In the first method rigid-rotation is invoked to determine I_L from the value of I_H extracted from the out-of-plane alpha distributions. In the second method, we utilized the experimental γ -ray multiplicity and the relation, $I_L + I_H = 2(M_\gamma - 5) + I_p$, to determine the sum of the spins. The corrections (I_p) for the angular momentum removed by neutrons and alpha particles were done following the prescription described in Ref. 13. The agreement between the spins derived from M_γ and those derived from the out-of-plane α -distributions is quite good.

In summary, we have studied the transfer of angular momentum into intrinsic spin and its partitioning within the di-nuclear complex. These data provide the first unambiguous evidence for rigid rotation of the intermediate complex in this mass region. Furthermore, large deformations are indicated by three sources: fragment kinetic energies, spins extracted from alpha distributions and those deduced from gamma multiplicity data. It should be mentioned that methods of reproducing the fragment kinetic energies employing smaller deformations and a separation or thin neck fail to convert enough orbital angular momentum into intrinsic spin to be consistent with the experimental data.

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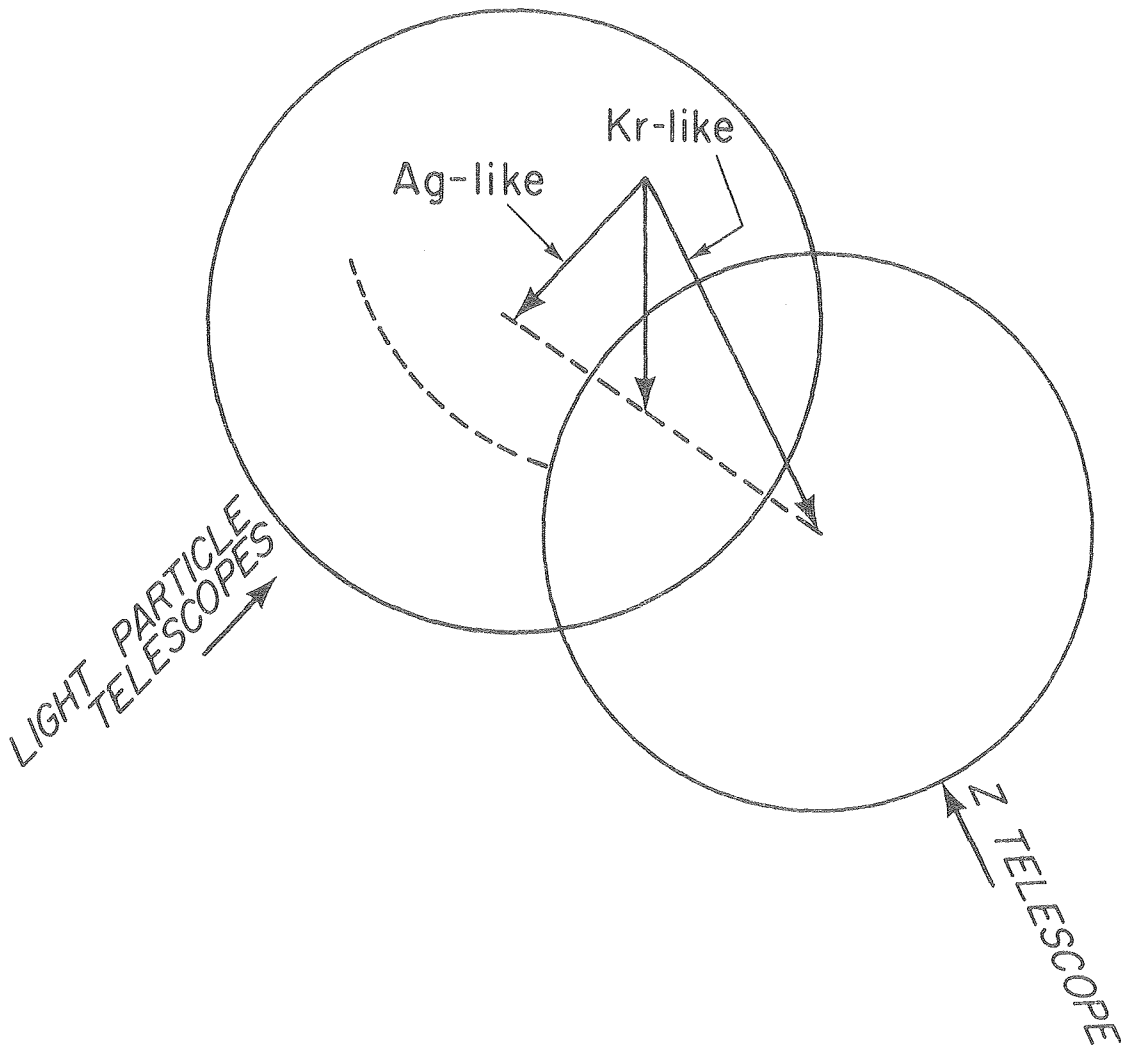
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Figure Captions

- Fig. 1 Vector diagram for the reaction system. Circles are for 1 Coulomb barrier α -particle emission. For the light-particle telescopes an arrow indicates their in-plane projection and a dashed arc their detection threshold.
- Fig. 2 Alpha particle angular distributions as a function of out-of-plane angle for several Z-bins. Each bin is 3 Z units wide and is labelled by the median Z value. The distributions without any coincident γ -ray requirement a) are expressed in units of differential multiplicity.^{4,5} Whereas the distributions with two or more coincident γ -rays b) are normalized to those in a) at 90° for the same Z bin.
- Fig. 3 a) Center-of-mass energies as a function of the charge of the light fragment. The width of the symbols indicate the uncertainty in the primary charge (before evaporation). The curves are calculations for two spheroids in contact and are labeled by the ratio of axes. b) Spin of the heavy fragment extracted from its associated out-of-plane α -distribution. Calculations for rolling and rigid rotation of spheroids are indicated. c) Sum of the two spins of the deep-inelastic fragments as determined from the out-of-plane α -distributions (closed) and M_γ (open).

$^{nat}\text{Ag} + ^{84}\text{Kr}$ (664 MeV)



XBL 804-549

Fig. 1

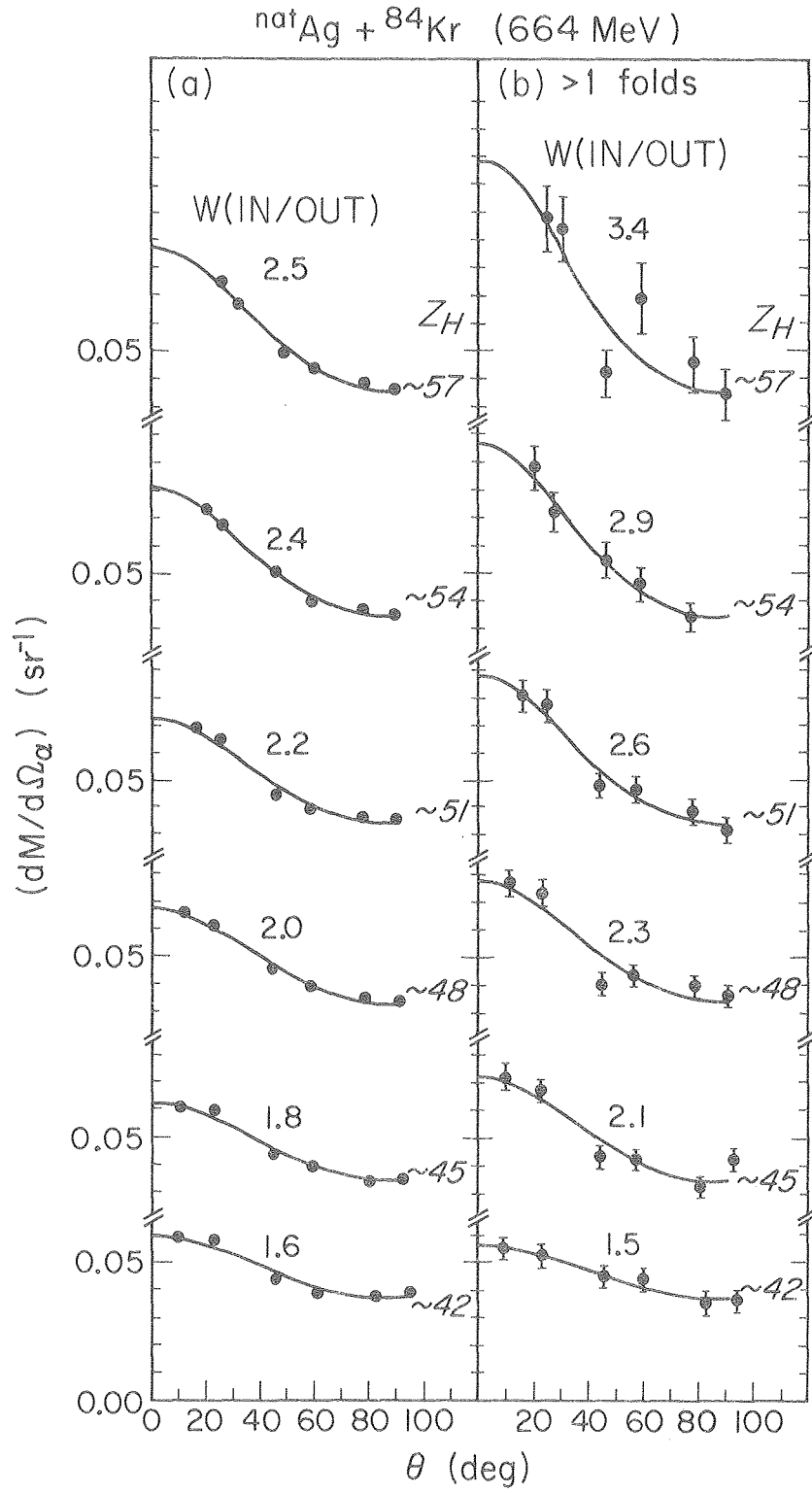


Fig. 2

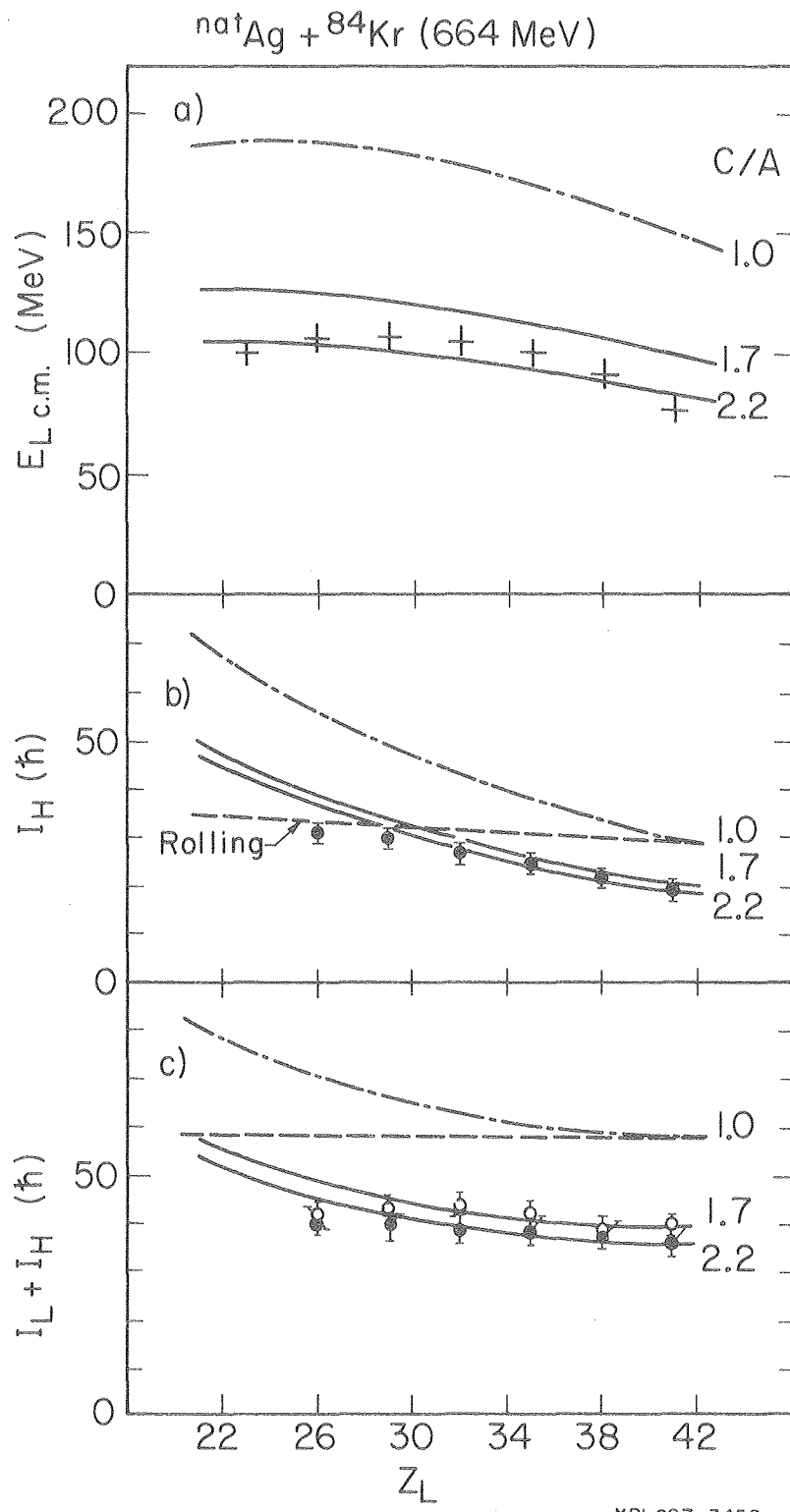


Fig. 3