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Tangential Friction in Deep-Inelastic Scattering of ^{16}O from Nickel

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Bombarding Ni targets with 96-MeV ^{16}O ions, we have observed deep-inelastic groups of mass-16 and -12 reaction products with Q values centered at -30 to -35 MeV. From the multiplicity of the coincident γ de-excitation, total fragment spins and hence, using a classical model, orbital angular momentum transfers of $12\hbar$ to $15\hbar$ are deduced. These, and at least 50% of the energy dissipation, are ascribed to tangential friction.

Recent studies of collisions induced by heavy projectiles, e.g., ^{40}A and ^{84}Kr, with heavy targets at energies well above the Coulomb barrier have revealed[1] a new type of reaction mechanism. The terms deep-inelastic scattering or transfer, quasi fission, or strongly damped collisions have been used to describe processes which have in common a large dissipation of the entrance-channel kinetic energy. In the attempts to describe these processes by the action of frictional forces, the importance of tangential friction, causing a loss of orbital angular momentum, is widely discussed,[2,5] while no experimental information seems to exist on this point. In this Letter, we first show that deep-inelastic scattering occurs also for the ^{16}O+Ni system at 6 MeV/A which is a much lighter target-projectile system than those for which this process has been observed so far. Second, we present a measurement of the multiplicities of γ rays emitted by the reaction products from which we deduce the fragment spins and hence the energy loss due to of tangential friction.

At the upgraded[6] Heidelberg MP-type Van de Graaff tandem accelerator a beam of 96-MeV ^{16}O was used to study the reactions induced in a 1.3-mg/cm^2 nickel target. The light reaction products were measured at laboratory scattering angles between 25° and 55° with a time-of-flight arm of 80 cm length. The time-start signal was derived from a 0.5-mg/cm^2 scintillator foil, the energy and the time-stop signal from two 300-μm-thick Si detectors of 450 mm^2 area each. Three 3-in. × 3-in. NaI(Tl) detectors were placed 15 cm from the target and operated in coincidence with the particle detectors. One of the γ detectors was mounted in the scattering plane at $\theta_\gamma = 135°$ and two at $\theta_\gamma = 90°$ and azimuthal angles of

60° and 120° off plane. The time of flight, the particle energy, the γ-ray energy, and the time difference between the γ-ray arrival and the start signal were recorded event by event. The γ-ray multiplicity was determined from the coincident and singles counting rates measured simultaneously, according to

$$N_{\rm coinc}/N_{\rm sing} = M_\gamma \Omega_\gamma / 4\pi.$$

The energy dependence of the total efficiency $\Omega_\gamma/4\pi$ was reduced by placing absorber disks of 3-mm Pb and 3-mm Cu in front of the γ detectors and was determined to be 1.2% for the three detectors together, with a threshold set at $E_\gamma = 600$ keV. We found no significant change in M_γ when lowering this threshold by 200 keV in the computer analysis of the data and in the source spectra used for the efficiency calibration. The mean γ-ray energy in the experiment was about 1.4 MeV. The influence of Compton scattering from surrounding material on the coincident yield was found to be less than 15% and is approximately accounted for by the *in situ* efficiency calibration. Contributions from neutrons with $E_n < 9$ MeV can be excluded because of a time resolution of 3 nsec full width at half-maximum between particle and γ branch. Twofold coincidences lead to an additive correction $\Omega_\gamma M_\gamma(M_\gamma - 1)/4\pi$ to M_γ which amounts to 0.36 for $M_\gamma = 6$. An averaging of the particle-γ angular correlation is accomplished by the summation of the coincidence yields of the three detectors. Regarding all the corrections, we estimate a nonstatistical error of 15% for M_γ.

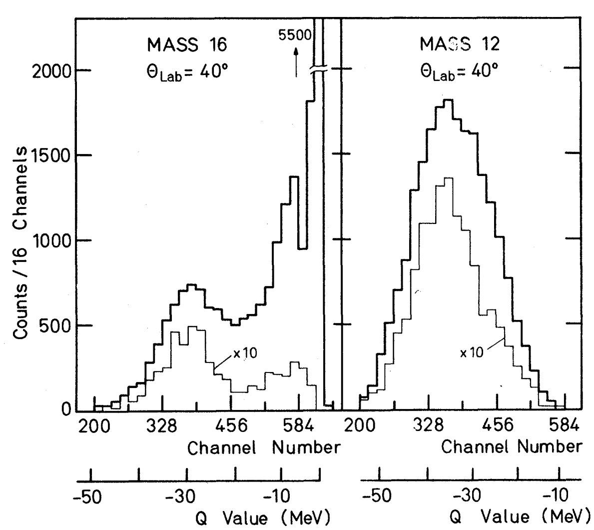

FIG. 1. Energy spectra of mass-16 and mass-12 reaction products from $^{16}O + Ni$ at 96-MeV bombarding energy, both free (heavy lines) and in coincidence with γ rays (light lines). Sixteen channels correspond to 2.0-MeV lab energy, 3800 counts in the free spectra equal 1 mb/sr.

In Fig. 1 singles and coincident spectra are displayed for masses 12 and 16. These masses make up more than 90% of the reaction products with $4 < A < 30$ at all scattering angles. By correcting for energy losses in the target and in the foils we obtain the reaction Q values assuming two-body kinematics. At all angles $\theta_{\rm lab} > 30°$, a pronounced deep-inelastic group is observed in the mass-16 spectra which centers at $Q = -30$ MeV and is well separated from the quasi-elastic peak at more positive Q values. In the mass-12 spectra, the deep-inelastic group is centered around $Q = -35$ MeV with a cross section about 3 times larger than that of the mass-16 group. Spectra for masses in between 12 and 16 also exhibit a similar deep-inelastic group with $Q \approx -30$ to -35 MeV, but with cross sections one order of magnitude smaller. Towards more forward angles, the separation from the quasi-elastic group is lost in the mass-16 spectra, and the group in the mass-12 spectra becomes more asymmetric, with the center moving towards more positive Q values. The center of the deep-inelastic reaction group is about 10 MeV above the Coulomb barrier $[R_C = 1.4(A_1^{1/3} + A_2^{1/3})$ fm$]$ for both the $^{16}O + Ni$ and the $^{12}C + Zn$ systems.

Differential cross sections are shown in Fig. 2 for three regions of the spectra labeled by different Q values. It is seen that the angular distribution of the deep-inelastic group is significantly flatter than that of the quasi-elastic events and that of the intermediate energy range. This fea-

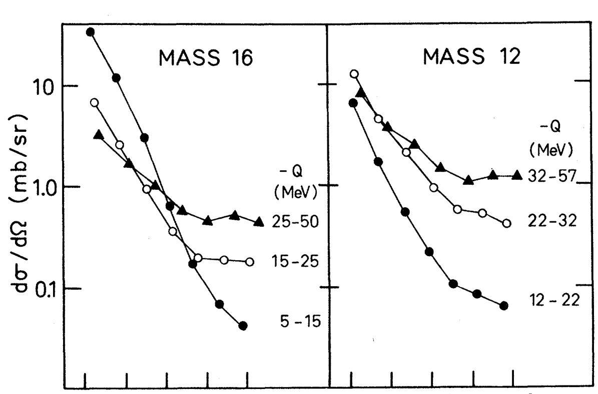

FIG. 2. Differential cross sections versus center-of-mass scattering angle for mass-16 and -12 products for three regions of the spectra, labeled by the Q values.

ture is similar to that observed by Artukh *et al.*[1] and has been interpreted by Wilczynski[2] as nuclear orbiting of frictioning nuclei. Integrating $d\sigma/d\theta$ for the deep-inelastic mass-16 and -12 reaction products for $\theta_{\text{c.m.}} = 30°$ to $70°$ and extrapolating to 0° and 180°, we a get a rough estimate of 80 mb. In contrast to the experiments at higher energies,[1] this is still a small fraction of the calculated[7] total reaction cross section of 1800 mb.

The measured γ-ray multiplicities are shown in Fig. 3. The deep-inelastic events have significantly higher multiplicities than the quasi-elastic events, with $M_\gamma \approx 5$ for mass 16 and $M_\gamma \approx 6$ for mass 12. The relatively large multiplicities for the quasi-elastic mass-12 group probably reflect effects of the mass transfer.

To relate the measured values of M_γ to the initial fragment spins I, we use Mollenauer's measurement[8] of M_γ for Cu compound nuclei found by the α + Co and ^{12}C + V reactions. The measured M_γ is a function of I primarily but, because of light-particle evaporation, it is also a function of the excitation energy E_x. To first order, $\Delta I = (\partial I/\partial M_\gamma)\Delta M_\gamma + (\partial I/\partial E_x)\Delta E_x$. It is found[8] that $M_\gamma = 6.3$ corresponds to an average spin of $18\hbar$ for $E_x \approx 49$ MeV. A linear interpolation using $(\partial I/\partial M_\gamma) \approx 2\hbar$ and $(\partial I/\partial E_x) \approx 3\hbar/16$ MeV from Ref. 8 yields for the centers of the mass-12 and -16 deep-inelastic groups $I \approx 15\hbar$ and $I \approx 12\hbar$, respectively. Since the E_x and I values of our experiment lie in between those of Ref. 8, it is reasonable to use the compound-nucleus experiments as a calibration for deep-inelastic reactions leaving the fragments presumably in a narrower spin distribution. To include γ emission from the light fragments, it is verified from the decay schemes for ^{12}C and ^{16}O (being the most likely candidates for the mass-12 and -16 reaction products) that for levels stable against α and nucleon decay, M_γ will be close to 1 and I_1 close to $1.5\hbar$, on the average. Moreover, since in any classical model of the friction process, the fragment spins, I_1 and I_2, and the orbital angular momenta, l_i and l_f, are all oriented in parallel, we arrive at the same values of about $12\hbar$ and $15\hbar$, respectively, for the *total* spin $I = I_1 + I_2$, being equal to the angular momentum transfer $l_i - l_f$ during the collision.

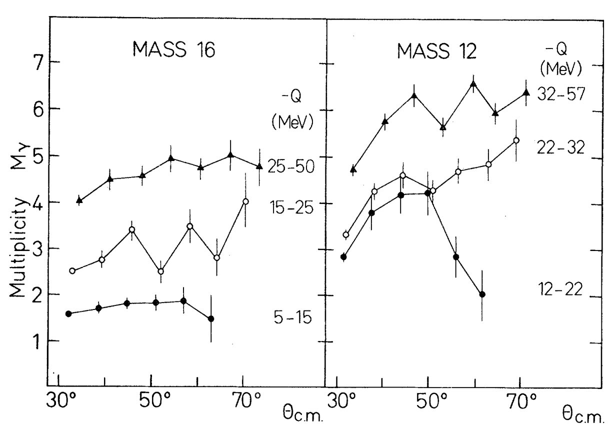

FIG. 3. The γ-ray multiplicity M_γ versus center-of-mass scattering angle for mass-16 and -12 products of different Q values. Deep-inelastic events (triangles) stand out by having the largest M_γ. Error bars indicate statistical errors only.

We wish to discuss these results in a semiclassical framework, neglecting quantum-mechanical effects that may disturb the maximum alignment. In such a description of deep-inelastic scattering, the transfer of orbital angular momentum is ascribed to the action of a tangential friction force. More specifically, from the measured mean kinetic energies and the change of orbital angular momentum, we may draw three conclusions:

(i) For mass 16, we split the observed Q value into two parts corresponding to tangential and radial friction,

$$Q_{\text{exp}} = Q_{\text{tan}} + Q_{\text{rad}}.$$

For simplicity of the argument we assume that the forces act at a certain distance R. Then

$$Q_{\text{tan}}(R) = (l_f^{\,2} - l_i^{\,2})/2\mathcal{J}(R),$$

where $\mathcal{J}(R) = \mu R^2$ is the relative moment of inertia. To derive a lower limit of $|Q_{\text{tan}}|$ we replace l_i by its lower bound, the critical angular momentum $l_{\text{crit}} = 42\hbar$,[9,10] and R by its largest value, the grazing distance $R_{\text{gr}} = 9.8$ fm.[7] Inserting $l_i - l_f = 12\hbar$, we obtain $|Q_{\text{tan}}| \approx 15$ MeV which is 50% of the mean deep inelastic Q of -30 MeV. Inserting more reasonable distances smaller than R_{gr}, our data require larger values of $|Q_{\text{tan}}|$. For instance, with $R = 9$ fm, which is still considerably larger than proposed[9,10] fusion radii, we find that tangential friction accounts for 60% of the Q value observed. It should be stressed that these conclusions are free from any assumptions on nuclear potentials. On the other hand, if it is assumed that all radial energy available in the entrance channel is dissipated by radial friction, it is found that $Q_{\text{rad}} \approx Q_{\text{exp}} - Q_{\text{tan}}$ can be fulfilled for a reasonable choice[7,10] of nuclear potentials.

(ii) The large yield of mass 12 can be ascribed to the same friction process leading to an excitation of ^{16}O close to an effective α threshold in the composite system. The mass-12 fragments are unlikely to originate from breakup, since this process would yield less γ rays compared to ^{16}O de-exciting by γ emission—in contradiction to the higher M_γ observed. On the other hand, *transfer* of an α particle in the course of the friction process will transform more angular momentum of the relative to the intrinsic motion, resulting in a higher M_γ—in agreement with our data. Since considerably higher excitation of ^{16}O will be needed to transfer one or two nucleons, the low yield of masses between 12 and 16 is consistent with this picture. The larger value of $|Q|$ for ^{12}C in comparison to ^{16}O is approximately ascribed to the difference in rotational and Coulomb energies. It may also be noted that semiclassical matching of Coulomb trajectories is incapable of explaining the large negative Q value of the friction-induced transfer.

(iii) In a classical description of friction, Tsang[4] distinguishes between sliding, rolling, and sticking of the fragments to each other, leading to a value of l_f/l_i being larger than, equal to, or smaller than $\frac{5}{7}$, respectively. With all the reservations in mind concerning the implicit assumption of rigid-body moments of inertia even for the light fragments, it is tempting to visualize a process leading to the formation of a rotating nuclear molecule, generated by friction. With $l_i = 42\hbar$ and $l_i - l_f = 12\hbar$ for ^{16}O we find $l_f/l_i = 0.7$.

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Does the Fourth ψ Particle Exist at About 4.9 GeV?*

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We show that, in a generalized three-triplet quark model, there can be four new fundamental vector-meson states with the photon quantum numbers. We propose that the broad peak in the total cross section for e^+-e^- annihilation into hadrons at 4.1 GeV and the narrow resonances $\psi(3.1)$ and $\psi(3.7)$ account for three of these. We predict, among other things, that there exists a fourth resonance ($\Gamma \sim 300$ MeV) at about 4.9 GeV with a partial width to electrons of approximately 1 keV.

The Stanford Linear Accelerator Center–Lawrence Berkeley Laboratory e^+-e^- colliding-beam experiment[1] at SPEAR has recently revealed not only very narrow resonances $\psi(3.1)$ and $\psi(3.7)$ but also a broad enhancement of the total cross section at the center-of-mass energy $\sqrt{s} \approx 4.1$ GeV. If it is a single vector-meson resonance [which we call $\psi(4.1)$], its total width (Γ) and partial decay width to an electron pair ($\Gamma_{\psi(4.1)\to e^+e^-}$) are reported to be approximately 250–300 MeV and 4 keV, respectively. In