deep inelastic reaction products are actually found at somewhat smaller angles.

The fusion cross sections derived from these calculations are shown in Fig. 2(c) together with the experimental data. The good agreement may indicate that we have somewhat overestimated the effect of the surface degrees of freedom, since we have not included the additional damping due to particle transfer. We have also made a number of preliminary calculations including this damping through prescriptions of the type of Moretto and Schmitt[7] and of Blocki *et al.*[8] These results confirm that the reduction in the fusion cross section below the geometrical limit is due to the fact that at higher bombarding energies fusion at small impact parameters is dynamically inhibited (cf. also Broglia, Dasso, and Winther[9]). The calculations including transfer also indicate that the deflection function for the deep inelastic reaction products is shifted somewhat towards forward angles.

It is interesting that the tendency of the ions to "bounce off" for small impact parameters has been found also in time-dependent Hartree-Fock calculations.[10]

In order to obtain a unique signal of the predicted "bouncing off" of the projectile for low impact parameters, one might utilize the kinematics of heavy-ion reactions. If one assumes that the final total kinetic energy in the center of mass is approximately equal to the height of the Coulomb barrier E_B one finds that the projectile after a head-on collision is at rest in the laboratory system if the bombarding energy is

$$E_p = (1+r)r^{-2}E_B,$$

where r is the mass ratio of projectile to target nucleus. The small Doppler shift of the γ quanta from the de-excitation of the scattered projectile at this bombarding energy might be an interesting effect to look for.

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New Evidence for a Direct Process in the (e, α) Reaction

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Alpha-particle energy and angular distributions have been measured for the reaction ^{60}Ni$(e,\alpha)e'X$ using electrons of energies 33, 60, and 120 MeV. Statistical-model calculations give good quantitative agreement in the region of the peak of the α energy spectra. Higher-energy α particles exhibit a forward-peaked angular distribution and a cross section several orders of magnitude above the statistical-model predictions, indicating the presence of a direct-reaction component.

Alpha particles emitted by medium-weight nuclei which have been excited by real or virtual photons originate mainly from the statistical decay of the excited nucleus.[1-4] In heavy nuclei there is some evidence of a direct-reaction process,[2,5] but such a process has not been observed in medium-weight nuclei. In this Letter we present unambiguous evidence for the presence of both a direct-reaction (pre-equilibrium) component and an evaporation component in the $(e, \alpha)e'$ reaction on the medium-weight nucleus ^{60}Ni.

We have studied the α energy spectra and angular distributions of α particles emitted in the reaction ^{60}Ni$(e, \alpha)e'X$ at electron energies up to 120 MeV, using the University of Glasgow electron linear accelerator. The α particles were momentum analyzed with an $n = \frac{1}{2}$ double-focusing spectrometer,[6] of energy resolution 0.1%, and detected in an array of ten silicon surface-barrier detectors. Shielding around the detectors reduced the background to negligible proportions over most of the α energy range. The target was isotopically enriched ^{60}Ni, of 99.6% purity. Its thickness was found by α energy-loss measurement to be 696 ± 42 μg/cm^2. The total error in cross section due to uncertainties in the values of target thickness, electron current, spectrometer solid angle, and dispersion is $<7\%$.

Spectra of α particles emitted following electron bombardment at 33, 60, and 120 MeV are presented in Fig. 1. The solid lines in the figure are the results of a statistical-model calculation which relates the (γ, α) cross section to the (γ, n) cross section:

$$d\sigma_{\gamma,\alpha}(E_\gamma, E_\alpha) = \frac{\sigma_{\gamma,n}(E_\gamma)\,\Gamma_\alpha(E_\gamma, E_\alpha)\,dE_\alpha}{\int \Gamma_n(E_\gamma, E_n)\,dE_n}. \qquad (1)$$

Here the (γ, n) cross section has been approximated by using the measured[7] single-photoneutron cross section $[\sigma(\gamma, n) + \sigma(\gamma, pn)]$. This approximation is reasonable since in the region of our calculation $\sigma(\gamma, pn)$ is small compared with $\sigma(\gamma, n)$. The $(e, \alpha)e'$ cross section was then computed on the assumption that the $E1$ virtual-photon spectrum provides the dominant contribution to the excitation process:

$$d\sigma_{e,\alpha}(E_e, E_\alpha) = \int_{12}^{33} d\sigma_{\gamma,\alpha}(E_\gamma, E_\alpha) N^{E1}(E_e, E_\gamma) E_\gamma^{-1}\, dE_\gamma, \qquad (2)$$

where N^{E1} is the electric-dipole virtual-photon intensity spectrum calculated from the analytical expression of Wolynec, Onley, and Nascimento[8] which results from a fit to the distorted-wave calculations of Gargaro and Onley.[9] The neutron- and α-channel exit widths (Γ_n and Γ_α) were calculated with a modified version[10] of the computer code HAUSER,[11] based on conventional Hauser-Feshbach theory.[12] The optical-model parameters are taken from Wilmore and Hodgson[13] and Lemos.[14] The method of level-density calculation, and the parameters used, were those of Gilbert and Cameron.[15] The calculation takes no account of photon absorption above $E_\gamma = 33$ MeV, yielding only that part of the α energy spectrum which results from excitation of the target in the region of the giant dipole resonance.

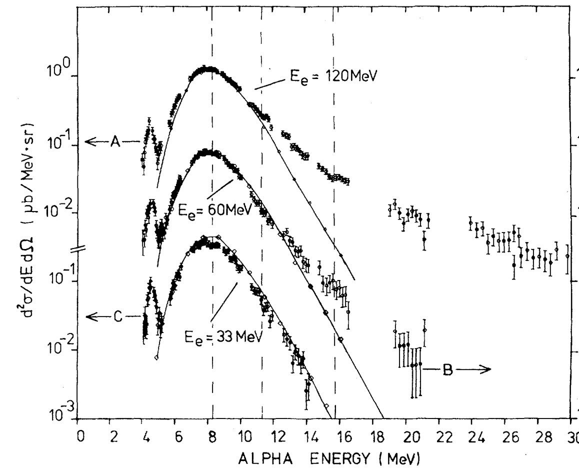

FIG. 1. Alpha-particle energy spectra at $\theta_\alpha = 90°$, for $E_e = 120$ MeV (curve A, upper left-hand scale), $E_e = 60$ MeV (curve B, right-hand scale), and $E_e = 33$ MeV (curve C, lower left-hand scale). Errors shown are absolute. The solid lines are the results of a statistical calculation assuming photon absorption below $E_\gamma = 33$ MeV. The dashed lines mark the mean energies at which angular distributions were taken.

This method of calculating the $(e, \alpha)e'$ cross section can be used only in regions above the neutron threshold. The sudden drop in observed cross section above 4.3 MeV is due to the onset of neutron emission: α particles of lower energy doubtlessly result almost entirely from the compound-nuclear excitations below the neutron separation energy of 11.4 MeV.

The statistical-model calculations are seen to give good agreement with the magnitude and position of the peak of the α spectrum at all three electron energies. For E_α in the range 6–12 MeV the discrepancies do not exceed ±50%, which is within the inherent uncertainty of our evaporation calculation. Above $E_\alpha = 12$ MeV, comparison of the measured and calculated energy spectra shows dramatic differences; a high-energy tail in the spectrum becomes systematically larger compared to the evaporation calculation as the electron energy is increased. Whereas the observed spectrum agrees with the calculation at $E_e = 33$

MeV, it exceeds it by several orders of magnitude at $E_e = 120$ MeV. Although slight changes in the calculation input parameters could improve agreement in the absolute magnitude of the cross section in the 6–12-MeV region, it is unlikely that such a procedure would improve the fit significantly above $E_\alpha = 12$ MeV.

Clearly there exists a further component in the $(e, \alpha)e'$ reaction, in addition to the evaporative part resulting from excitation of the target by photons of $E_\gamma \leq 33$ MeV. Further evidence on the nature of this component has been obtained by measuring α-particle angular distributions. Data obtained at $E_e = 120$ MeV are presented in Fig. 2; similar results have been obtained at $E_e = 60$ MeV.

The angular distribution for α energy, 8.2 MeV, in the peak of the evaporation spectrum is symmetric about 90°, as expected of particle emission proceeding through compound-nucleus states. However, at higher α-emission energies the angular distributions become increasingly forward peaked, suggesting that a larger fraction of the α-emission process is associated with a direct-reaction process. Angular distributions similar to those for ^{60}Ni have been obtained by us for ^{56}Fe. These distributions show, for the

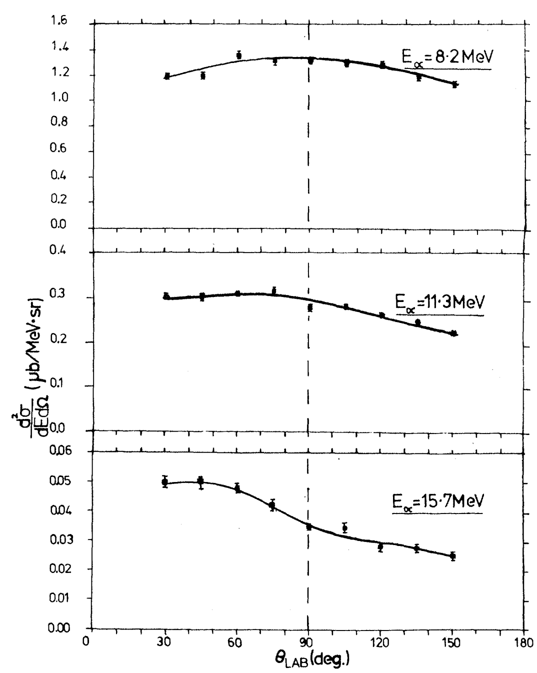

FIG. 2. Alpha-particle angular distribtuions at $E_e = 120$ MeV averaged over the α energy ranges 7.7–8.7 MeV, 10.6–11.9 MeV, and 14.8–16.4 MeV. Errors shown are relative. The solid lines are merely to guide the eye.

first time in medium-weight nuclei, the smooth change from a symmetric to an asymmetric angular distribution as the α-emission energy increases.

The evaporative component of our α energy spectra is well explained in terms of $E1$ virtual-photon absorption to a compound giant resonance state which undergoes statistical decay. It has been claimed[16] that in heavy nuclei, at least, the α-emission process proceeds dominantly through $E2$ transitions. It is possible that the evaporative component observed here can be explained entirely in terms of photon absorption to the $E2$ isoscalar resonance, positioned[17] at about $E_x = 16$ MeV in ^{60}Ni. The magnitude of our cross sections would then require the α-emission channel to exhaust 75% of the $E2$ energy-weighted sum rule.[18] The $E2$ virtual-photon intensity was obtained from the computer code of Gargaro and Onley, as used in Ref. 9. However, such a process still would fail to reproduce the high-energy tail seen in the α-energy spectra. Consideration of the angular distributions makes it unlikely that the $E2$ isovector resonance contributes to the high-energy α spectrum. The overlap of the $E1$ resonance centered at 20 MeV and the predicted $E2$ isovector resonance at ~33 MeV would probably not be sufficient to produce the necessary interference terms required to explain the observed forward-peaked angular distributions.

It has been assumed previously that an evaporative process would dominate α emission following the absorption of high-energy photons; for example, an attempt has been made to fit α energy spectra from targets irradiated by 450-MeV bremsstrahlung with calculated evaporation spectra.[19] However, there are several inherent difficulties with such a calculation. Above ~30 MeV photon energy a pre-equilibrium cascade becomes increasingly probable, leading to a final compound-nucleus energy below the initial excitation energy. The cross section for photon absorption leading to compound-nucleus formation is uncertain above ~30 MeV, and even if we assume knowledge of this cross section, difficulties arise with the validity of level-density formulas at high excitation energies. Therefore the questionable validity of evaporation calculations based on a compound nucleus at excitation energies above ~30 MeV led us to cut off the statistical-model calculations at 33 MeV excitation. Since such calculations predict angular distributions symmetric about 90°, the observed forward-peaked angular distributions for high-energy α's will not be reproduced, even at high-excitation energies. It seems more probable that an intranuclear cascade initiated by high-energy nucleons from (γ, N) processes (such nucleons themselves being strongly forward peaked) is responsible for the high-energy α emission. The cascading nucleons could then eject α particles in a similar reaction mechanism to the (n, α) and (p, α) reactions. Recent work[20] on these (N, α) reactions has yielded a satisfactory explanation of the observed energy spectra, which are similar in form to those observed here. Currently an attempt is being made to interpret our $(e, \alpha)e'$ data in terms of the (N, α) results.

It can be seen from Fig. 1 that the increase in electron energy from 60 to 120 MeV causes an order of magnitude increase in the observed cross section for high-energy α particles ($E_\alpha \sim 18$ MeV). The ratio of virtual-photon intensity at these two energies, for $E_\gamma = 30$ MeV, is 1.6. The high-energy α particles are therefore unlikely to result from a single-step direct reaction mechanism involving the virtual photon.

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Evolution of Turbulence from the Rayleigh-Bénard Instability

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Measurements of heat transport through horizontal layers of fluid heated from below are reported for three aspect ratios Γ ($\Gamma = D/2d, D =$ diameter, $d =$ height of the cylindrical cells). They show that for $\Gamma = 57$ the fluid flow is turbulent, in the sense that it has an a nonperiodic time dependence, for numbers $R > R_t$ with $R_t \cong R_c$ (R_c is the critical R for onset of fluid flow). For $\Gamma = 4.72$, we find $R_t \cong 2R_c$. For $\Gamma = 2.08$, a quasiperiodic state exists for $R_p \leq R \leq R_t$, with $R_p \cong 10R_c$ and $R_t \cong 11R_c$.

A problem of considerable interest is the manner in which nonperiodic time-dependent flow (turbulence) evolves in a fluid subjected to an external stress.[1-10] We report here on an experimental investigation of this phenomenon in the case of a horizontal fluid layer contained in a cylindrical geometry and heated from below. We find that the sequence of events leading to turbu-