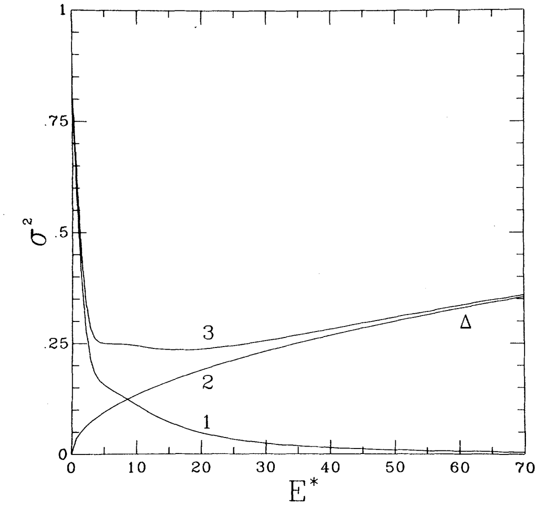

FIG. 1. Energy dependence of the quantal (curve 1) and of the classical statistical width (curve 2). Curve 3 represents the sum of both widths and the point indicates the experimental value.

$=(6/\pi^2)\times A/10\ \mathrm{MeV}^{-1}$.

The second moment of the quantal distribution σ_z^2 versus excitation energy is given in Fig. 1. The narrowing of the distribution with increasing energy is quite evident. Since this calculation does not include thermal fluctuations, which correspond to the fluctuating part of the wave function, they are introduced in the simplest way,

$$\sigma_z^2=\sigma_{z,Q}^2+\sigma_{z,T}^2,$$

where the labels Q and T stand for quantal and thermal. The thermal width can be rigorously estimated by the same techniques as for the fluctuating cross sections in the statistical theory. It depends on the level densities only. The estimate which we gave for the thermal fluctuations corresponds to classical Boltzmann statistics.

The possibility of experimentally observing the minimum of σ_z^2 and its rapid rise with decreasing energy is of extreme importance because it would provide us with information on the damping of a giant resonance in a hot nucleus. This is particularly true in view of the extremely difficult alternatives, like γ decay from highly excited nuclei, etc.

The only experimental result shown in the figure is a heavy-ion example. Similar data are available in fission. Of course they do not prove our point. Until we can be assured that our guess for $\hbar\omega$ is a reasonable one (within a factor of 2), the experimental data should be considered as circumstantial evidence in favor of the present theory. Further theoretical work and experimental measurements at energies closer to the barrier will eventually tell the rest of the story.

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Origin of Gross Structure in $^{12}C+^{12}C$ and $^{16}O+^{16}O$ Inelastic Scattering

R. L. Phillips, K. A. Erb, and D. A. Bromley
A. W. Wright Nuclear Structure Laboratory, Physics Department, Yale University, New Haven, Connecticut 06520

and

J. Weneser[(a)]
A. W. Wright Nuclear Structure Laboratory, Physics Department, Yale University, New Haven, Connecticut 06520, and Brookhaven National Laboratory, Upton, New York 11973

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A nonresonant diffraction-model calculation is found adequate to describe the gross-structure behavior thus far observed in the $^{12}C+^{12}C$ and $^{16}O+^{16}O$ inelastic scattering excitation functions.

The prominent gross structures observed[1-3] in the single and mutual inelastic excitation yield of the 2^+ first excited state of ^{12}C in $^{12}C+^{12}C$ collisions have been discussed in terms of carbon-carbon molecular resonances.[1,4] Similar gross-structure behavior has been found in the cross sections for the $^{12}C + ^{20}Ne$ rearrangement[5] and the $^{16}O + ^{16}O(3^-)$ inelastic[6] exit channels resulting from $^{16}O + ^{16}O$ collisions, suggesting that such phenomena may occur frequently in the interactions of composite nuclei. The implications concerning molecular resonance phenomena could be highly significant; it is therefore important to determine the extent to which nonresonant mechanisms could be responsible for such gross structure. In the present Letter we investigate this question with particular reference to $^{12}C + ^{12}C$ and $^{16}O + ^{16}O$ inelastic scattering.

The measured inelastic- and the corresponding elastic-scattering cross sections share certain revealing characteristics: (1) In both channels broad cross-section enhancements several MeV wide and spaced several MeV apart are observed —as might be expected if the enhancements reflected the dominance of successive grazing partial waves in the entrance channel. (2) The elastic and inelastic angular distributions both tend to be highly oscillatory. The inelastic differential cross sections, however, become *less* oscillatory at energies corresponding to maxima in the total inelastic-scattering excitation functions. (3) The magnitudes of the cross sections involved in the inelastic gross structures are large, exhausting in some cases 50% of the maximum, or geometric, cross section associated with a single, surface-grazing, partial wave. These features provide clues to the nature of the underlying physical mechanisms.

Earlier studies have described these characteristic features within the framework of models which invoke broad, single-particle, shape resonances in the relative motion of the colliding nuclei.[7,8] In contrast, we shall examine a parametrization of the elastic scattering in terms of strictly nonresonant amplitudes, and use the Austern-Blair[9] relationship between elastic and inelastic amplitudes to deduce an energy dependence for the inelastic cross sections.

The main components of the phenomenological analysis of the elastic scattering of these nuclei[10-13] are the strong absorption of the lower, or interior, partial waves and the transparency or weak absorption experienced by surface-grazing waves. As a result of these properties, elastic scattering at energies well above the Coulomb barrier is dominated by diffractive processes which can be described using the smooth-cutoff parametrization of the elastic S matrix:

$$S_L = \eta_L \exp(2i\delta_L), \quad \eta_L(E) = \{1 + \exp[(E - E_G)/\Delta]\}^{-1}, \quad \delta_L(E) = \delta_{\max}[1 - \eta_L(E)],$$

with $E_G = E_0 + (\hbar^2/2\mathscr{I})L(L+1)$. The parameters were chosen with reference to the successful optical-model calculations of Gobbi *et al.*[11] (for $^{16}O + ^{16}O$) and of Reilly *et al.*[13] (for $^{12}C + ^{12}C$), in order to fix the energies at which the reflection coefficients equal 0.5. The maximum phase, $\delta_{\max}$, was varied to achieve reasonable fits to the total inelastic yields; $\delta_{\max}$ remained well below its resonance value. In fact, $\delta_{\max}$ never exceeded 60°, and this, together with the smooth variation of the η_L, guarantees the absence of resonances. The parameters adopted for $^{12}C + ^{12}C$ ($^{16}O + ^{16}O$) are $E_0 = 2.6$ (7.5) MeV; $\hbar^2/2\mathscr{I} = 107$ (55) keV; and $\delta_{\max} = 1.0$ (0.5) rad. The width parameter Δ was chosen to reflect the observation that for these light, identical-nucleus systems in which alternate partial waves are necessarily absent, only one partial wave is active in the elastic channel at any given energy. Within this restriction, the precise value assigned to Δ was treated as a free parameter. For both systems the parameters closely reproduce the positions of the "$n = 0$ molecular band" deduced by Arima, Scharff-Goldhaber, and McVoy[14] and independently by Fink, Scheid, and Greiner,[7] although our choice of parameters precludes any resonant behavior in the calculated yields.

The inelastic amplitudes were calculated using the Austern-Blair model, according to the prescription of Hahne[15]:

$$f_m^{\,I}(\theta) = \frac{1}{2i}\left(\frac{k'}{k}\right)^{1/2} \beta_I R \sum_{L,L'} (2L'+1)^{1/2} \exp[i(\sigma_L + \sigma_{L'})] \left\{\frac{\partial}{\partial L}[\eta_L \exp(2i\delta_L)]_E \frac{\partial}{\partial L'}[\eta_{L'} \exp(2i\delta_{L'})]_{E'}\right\}^{1/2}$$
$$\times \langle L'I00|L0\rangle\langle L'I-mm|L0\rangle Y_{L'}^{-m}(\theta,0).$$

The origin of the energy dependence of the $^{12}V + ^{12}C$ inelastic yields in the present calculation is illustrated in Fig. 1. The model cross sections show maxima whenever both $\partial\eta_L/\partial_L$ and $\partial\eta_{L'}/\partial_{L'}$, evaluated at the appropriate entrance- and exit-channel energies, are appreciable. Consideration of the figure suggests that gross structure generally may be anticipated in an inelastic excitation function whenever the interaction is localized in angular momentum and the Q value permits a significant energy

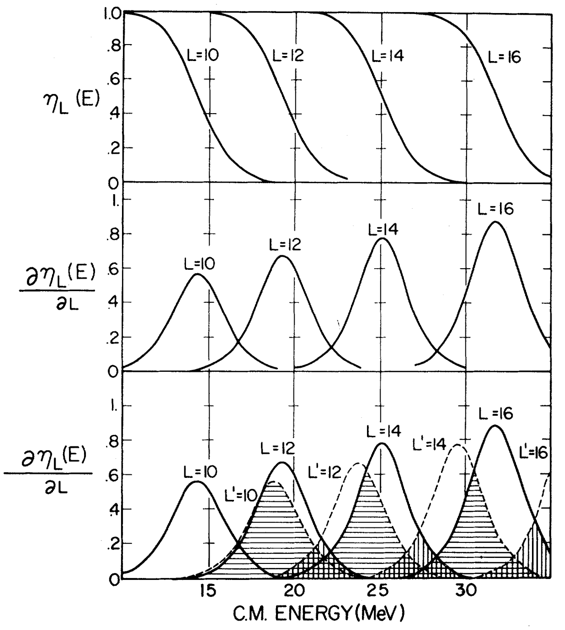

FIG. 1. Energy dependence of the elastic-scattering parameters, η_L, and their derivatives $\partial\eta_L/\partial_L$, for the ^{12}C + ^{12}C* (4.43 MeV) calculation with $\Delta = 1.0$ MeV and $\delta_{\max} = 0$. For the exit channel, $\partial\eta_{L'}/\partial_{L'}$ is evaluated at $E' - 4.43$ MeV (dashed curve). The shaded areas in the lower panel designate contributions to the inelastic yields with $L' = L - 2$ (horizontal shading) and $L' = L$ (vertical shading).

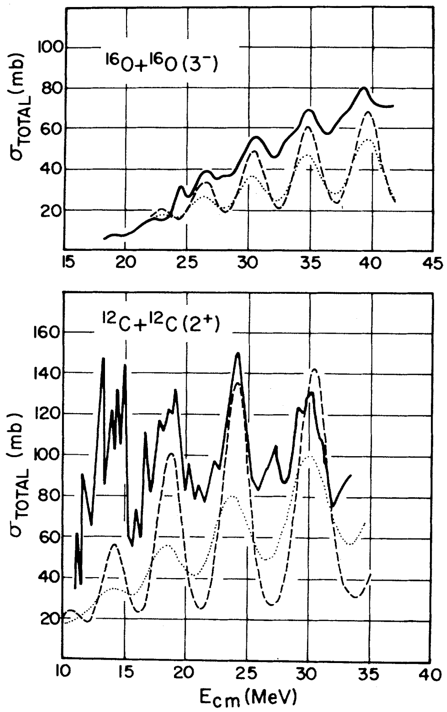

FIG. 2. Measured and calculated total inelastic-scattering cross-section excitation functions. The data are represented by solid lines. The dashed curves were calculated with $\Delta = 1.0$ MeV, and the dotted curves with $\Delta = 1.2$ MeV (^{16}O + ^{16}O) or $\Delta = 1.5$ MeV (^{12}C + ^{12}C).

overlap of the derivatives as illustrated by the shaded regions in the lower panel of Fig. 1.

It is interesting to note that in the example illustrated, the energy displacement of the exit-channel derivatives, reflecting the large negative Q value, requires that $L' = L - 2$, algebraically, for maximum cross section and hence results in a strong alignment (not a polarization) of the intrinsic spin of the excited residual nucleus.

The same analysis for the ^{16}O + ^{16}O system would give a similar result for the lowest strongly collective excitation, except that in this case $L' = L - 3$ would dominate. Data (e.g., angular distributions and correlations) are not yet available to test these predictions.

The calculated angle-integrated cross sections are compared, in Fig. 2, with the corresponding measured ^{12}C + ^{12}C (Ref. 1) and ^{16}O + ^{16}O (Ref. 6) inelastic-scattering excitation functions. Gross structure emerges clearly from the calculation; it is in general accord with that found in the data. Moreover, the magnitudes of the cross sections are reproduced, using previously measured[16] values of 1.78 and 1.57 fm for the deformation lengths of the 2^+ and 3^- excitations, respectively. The agreement between experiment and calculation leads us to conclude that the gross structure in the inelastic-scattering excitation functions can be understood most simply as a generalized diffraction phenomenon, and that its presence provides no evidence for the existence of quasimolecular resonances. Signatures reflecting the presence of the latter should be sought, instead, in deviations from simple gross structure. For the ^{12}C + ^{12}C interaction, evidence of such nondiffractive behavior may be inferred from the fragmentation of the gross structure into narrower components,[17] particularly in the low-energy data of Fig. 2.

This model success in the case of simple inelastic scattering immediately suggests its application to the mutual inelastic-scattering data available, as yet, only in the carbon system. We have found that the general features of these data also can be reproduced; these calculations will be described in a future publication.

Additional support for the general validity of the present calculation results from a consideration of the limited angular-distribution data now available. In Fig. 3 we compare calculated angular distributions (using $\Delta = 1.0$ MeV) with the inelastic $^{12}C + ^{12}C$ data of Wieland *et al.*[3] The forward-angle oscillations in the data are well reproduced by the calculation, as is the characteristic tendency toward damping of the angular-distribution oscillations (other than in the region of 90°) at energies corresponding to total-cross-section maxima. This tendency can be easily understood in a high-angular-momentum limit where $|\sin^{1/2}\theta Y_L^m(\theta)|^2$ oscillates as $|\cos[(L+1/2)\theta - \pi/4 + m\pi/2]|^2$, except at extreme angles, so that for even m values the arguments are $\pi/2$ out of phase with those for odd m values. Further, if only a particular *pair* of incoming and outgoing partial waves, L and L', enter, the Clebsch-Gordan coefficients are such as to weight even and odd m values equally, provided that $L \neq L'$. In the analysis outlined above, the centrifugal and Q-value effects ensure that the lowest option, $L' = L - 1$, is strongly favored at energies where gross-structure maxima occur. Here the equal weighting applies with its concomitant featureless angular distributions. Between maxima several angular momenta contribute, and the oscillatory behavior remains.

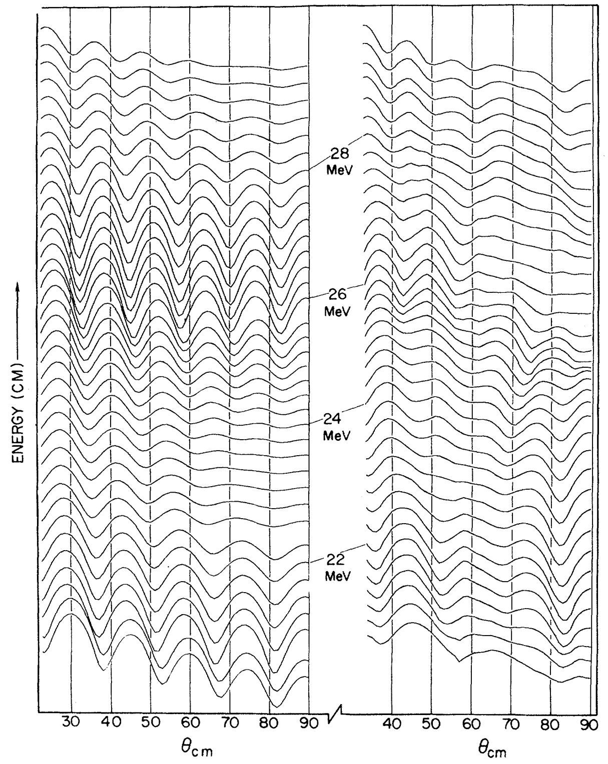

FIG. 3. Calculated (left panel) and measured (right panel) angular distributions for $^{12}C + ^{12}C^*$ (4.43 MeV) inelastic scattering. The data are from Ref. 3, energy averaged over a 1-MeV interval.

More than 90% of the angle-integrated 2^+ inelastic cross section appears forward of $\theta_{c.m.} = 70°$ and backward of $\theta_{c.m.} = 110°$; these yields are well described in the present calculation. An indication of phenomena not included in the model appears, however, in the angular region $70° \leq \theta_{c.m.} \leq 110°$. A similar inadequacy is evident in the $\theta_{c.m.} \approx 90°$ parametrized elastic scattering in that *unfragmented* gross structure is predicted, but with insufficiently enhanced peak-to-valley ratios. Both failures may signify the presence of interesting, nondiffractive phenomena.

In conclusion, in the present model, the inelastic gross structures arise as a simple consequence of energy-dependent angular momentum windows, and the maxima in the total cross sections can be associated with a particularly favorable kinematic matching between pairs of entrance- and exit-channel grazing partial waves. Similar gross structures may be anticipated in other heavy-ion reactions whenever these matching conditions are satisfied, although the structures are expected to be damped somewhat in nonidentical-particle systems where several entrance-channel partial waves may be active at any given energy. For the inelastic-scattering examples studied in the present Letter, the large cross-section magnitudes reflect, in addition to the matching, the collectivity of the inelastic excitations.

The results discussed above show that a nonresonant diffraction model is adequate to reproduce the gross-structure behavior thus far observed in the $^{12}C + ^{12}C$ and $^{16}O + ^{16}O$ inelastic-scattering excitation functions; this suggests that evidence for nuclear molecular phenomena must be sought in departures from such simple gross structure.

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(a) Permanent address: Brookhaven National Laboratory, Upton, N. Y. 11973.

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Observation of Mixed-Parity Electric-Dipole Oscillations in Charge Transfer to the $n=2$ Hydrogen Levels by Fast Protons in Gases

I. A. Sellin, L. Liljeby, S. Mannervik, and S. Hultberg
Research Institute of Physics, S-104 05 Stockholm, Sweden

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We find evidence for strong, collision-averaged excitation coherence between 2s and $2p_0$ amplitudes in charge transfer by fast protons ($v_i \approx 2$–3 a.u.) undergoing single collisions in He, Ar, and O_2. Quantum beat difference signals in Lyα (Eck beats) induced by reversible electric fields have amplitudes very similar to those seen earlier in C targets, supporting a "last-layer" (gas-layer?) hypothesis.

We have found a high degree of excitation coherence in electron capture to mixed-parity $n=2$ states by fast proton in gases. To our knowledge, there has been no previous experimental observation of such a phenomenon in charge transfer. Theorists working in the very active field[1] of charge transfer seem not to have concentrated on calculating the s-p capture amplitude differences as a test of various competitive theories of charge transfer. We show here that such phase differences are straightforward to measure for single ion-atom collisions, and hope that this paper will serve as a stimulus to calculation.

Since it was first shown in the work of Sellin *et al.*[2] that such mixed-parity excitation coherence is observable in beam-foil excitation, it has also been of interest to inquire whether such beats are induced by an exit surface capture or electric field effect as suggested by Eck[3] (characteristic of a solid-state effect) or whether such collision-averaged, mixed-parity state coherence is a prominent feature of charge transfer and perhaps other single ion-atom collision processes. Comparison of the character of electric dipole coherence in foil versus gas targets is then a promising tool for sorting out intrinsically solid state from binary ion-atom collision coherence phenomena.

In his original paper,[3] Eck proposed a simple technique for separating collision-averaged excitation coherence of H atoms from that induced by the electric fields required to couple levels of opposite parity, which otherwise do not decay to the same final state. The technique depends on applying reversible electric fields $\vec{E}$ parallel and antiparallel to the beam to exploit the fact that the excitation coherence quantum-beat signal is odd under reflection, whereas other signals are not. If there is an initial displacement of electron charge cloud with respect to the proton, or one develops in time because of an inequality in proton and average electron axial velocity, the displacement will be either enhanced or diminished depending on the direction of $\vec{E}$ relative to