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MOLECULAR STRUCTURE IN $^{12}C + ^{12}C$, ORBITING IN $^{12}C + ^{28}Si$, AND FIRST STUDIES OF THE $^{60}Ni + ^{60}Ni$ INTERACTION

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1. INTRODUCTION

The papers presented at this workshop have demonstrated convincingly that molecular resonances are not isolated quirks of nature, but rather, phenomena that occur in a very wide variety of nuclear reactions. Precisely because they are not quirks, and therefore not random, we can hope eventually to understand in detail why and where they appear. We are not yet at this stage. Yet, a very considerable body of data has accumulated, permitting us to begin to attempt to classify the resonances, to determine quantitatively how they relate to each other in a given system, and to study how their properties change from system to system. In the present paper, we discuss some physical implications of a recently proposed classification scheme for the $^{12}C + ^{12}C$ Coulomb barrier resonances for which the requisite very large body of experimental data is already available. We then present new data[1] suggesting that the back angle resonance-like structure previously observed in quasi-elastic $^{28}Si + ^{12}C$ reactions[2] reflects the existence of a fully developed, rotating di-nuclear system that governs back-angle yields in many additional exit channels. Finally, we discuss briefly some very recent data for $^{60}Ni + ^{60}Ni$ scattering in a first look at a previously unstudied region of the periodic table.

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2. CLASSIFICATION OF $^{12}C + ^{12}C$ COULOMB BARRIER RESONANCES

An enormous amount of work has gone into the study of the Coulomb barrier region of the $^{12}C + ^{12}C$ interaction, with the result that approximately forty resonances have been located below $E_{cm} = 13$ MeV and spin measurements made for at least 28 of these. A portion of the resonance spectrum, based on total reaction cross sections derived[3] from γ-ray measurements,[3,4] is shown in Fig. 1. Perhaps the most striking aspect of the spectrum is its remarkable complexity; if we did not know that many of the structures have greatly enhanced carbon-carbon partial widths, we might be tempted to conclude that no simple, quantitatively accurate description of this spectrum could be achieved. The large partial widths do strongly suggest that a two-body molecular interpretation should be at least approximately correct, however, and a molecular model in which the resonances are treated as quadrupole rotation-vibration excitations has met with qualitative success.[5] A possible analogy with atomic physics phenomena was drawn recently by Iachello,[6] who noted that diatomic molecules dominated by dipole degrees of freedom have the characteristic spectrum

$$E(v,L) = -D + a(v + 1/2) - b(v + 1/2)^2 + cL(L+1), \qquad (1)$$

where v and L denote vibrational and rotational quantum numbers, respectively. Although Iachello used group theoretical techniques, a similar result can be obtained by recognizing that whatever the detailed nature of the attractive forces that bind the nuclei into a molecular configuration, the corresponding potential can be represented in the region of its minimum at $r = r_0$ by the expansion

$$V(r) = V_0 + \tfrac{1}{2} A(r-r_0)^2 + B(r-r_0)^3 + C(r-r_0)^4 + \ldots.$$

The associated spectrum then has the form[7]

$$E(v,L) = \sum_{m,n} A_{mn}(v + 1/2)^m [L(L+1)]^n,$$

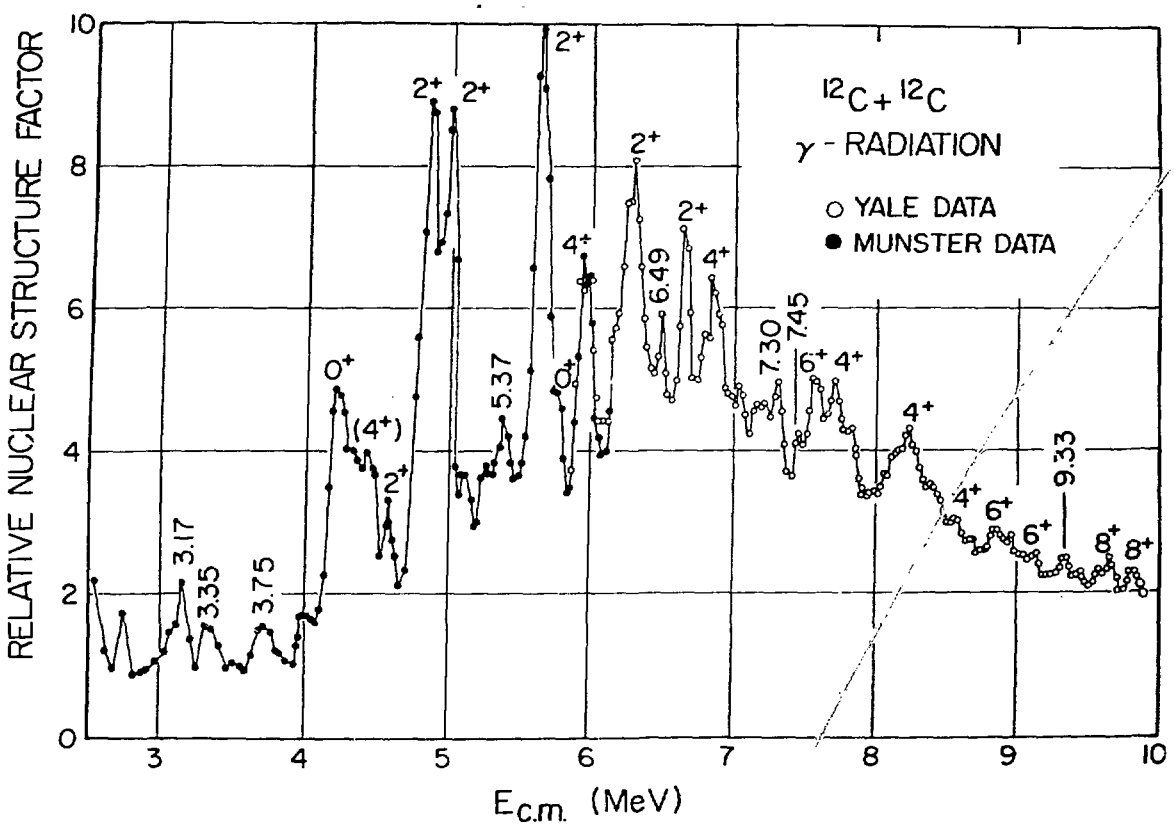

Fig. 1. Total γ-ray yields divided by Coulomb-centrifugal penetrability for the $^{12}C + ^{12}C$ reaction.

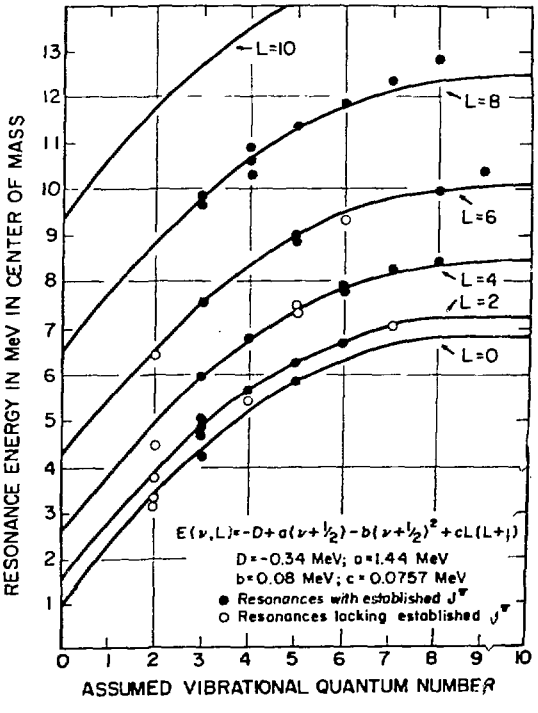

Fig. 2. Classification of known $^{12}C + ^{12}C$ resonances into rotational and vibrational bands.

which simplifies to Iachello's result when the summation is restricted to $m \leq 2$, $n \leq 1$ and rotation-vibration coupling is neglected. We found[8] that all available $^{12}C + ^{12}C$ resonance data below $E_{c.m.} = 13$ MeV can be described extremely accurately, even with this restriction, as is illustrated in Fig. 2. With only four parameters, we reproduce the energies of the 28 correlated resonances whose spins have been determined with an average rms deviation of 44 keV. The remaining 10 resonances, of unknown spin, can also be accommodated comfortably within this scheme by arbitrarily assuming appropriate spin assignments, and these are indicated by means of the open circles in Fig. 2. A more complete discussion of the calculation and a complete list of experimental citations may be found in Ref. 8; in the remainder of this section, we wish to point out some of the physical implications of our approach.

Several important properties of the binding potential corresponding to the theoretical spectrum can be deduced immediately from the parameter values listed in Fig. 2. (Many different parameter sets provide essentially equivalent fits to the data. In what follows, we restrict our discussion to those features of the potential that depend only weakly on the choice of parameter set.)

The rotational parameter, $c = 0.076$ MeV, interpreted in terms of an intrinsic configuration consisting of two point-like ^{12}C nuclei, implies an equilibrium separation of nearly 7 fm and a corresponding minimum in the binding potential at a radius far in excess of that implied by any reasonable $^{12}C + ^{12}C$ optical potential. Thus, this binding potential cannot describe the relative motion of two well-separated ground state ^{12}C nuclei. Chandra and Mosel[9] demonstrated some time ago, however, that the effective mass of the overlapping nuclei can be very much larger than the asymptotic reduced mass, and any such effect would move the deduced equilibrium separation radius toward a more acceptable smaller value. Nevertheless, the 24-nucleon system corresponding to this potential will obviously be very highly deformed, and it will be important in the future to investigate whether nuclear structure

calculations can encompass such highly deformed, quasi-stable configurations (s' pe isomers).

If such a quasi-stable configuration should exist at high excitation in ^{24}Mg, it is difficult to understand why negative parity states should be excluded from its rotational spectrum. None have been observed, but it should be noted that all resonance-sensitive experiments reported to date for this system have involved identical spin-0 bosons (^{12}C nuclei). Thus, negative parity resonances, even if present, could not have been observed. We suspect strongly that the next generation of experiments, involving reactions such as $^{20}Ne(\alpha,^{8}Be)^{16}O$, will reveal these states. If observed, and if their spectrum conforms to that found for the positive parity resonances, their presence will provide convincing evidence for a highly deformed molecular shape isomer in ^{24}Mg.

3. MOLECULAR ORBITING IN $^{12}C + ^{28}Si$ INTERACTIONS

The resonance-like behavior of the large-angle elastic and inelastic scattering yields[2] from collisions involving a variety of 1p and 2s-1d shell nuclei has posed an intriguing puzzle for some time now. While no detailed understanding of the phenomenon has emerged yet, we have very recently discovered that these anomalous quasi-elastic yields represent, at least for the $^{12}C + ^{28}Si$[10] and $^{12}C + ^{20}Ne$[11] systems, only part of the total large-angle cross section. The fraction of the total reaction cross section contributing to large-angle yields is much larger than had been realized, demonstrating the central importance of whatever processes are responsible and emphasizing that explanations based on the behavior of the elastic yields alone will probably be incomplete. The rather complete $^{28}Si + ^{12}C$ data to be discussed below provide strong evidence for the formation during the early stages of the collision of a well-developed orbiting di-nuclear molecule that exhausts nearly 25% of the total non-fusion cross section.

Excitation energy spectra for carbon, nitrogen, and oxygen reaction

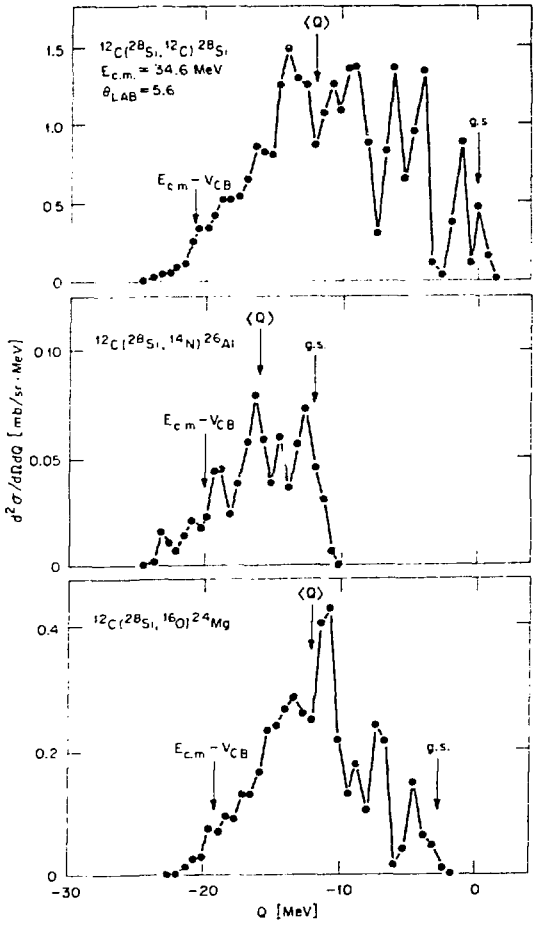

Fig. 3. Energy spectra for C, N, and O emitted at backward angles from the ^{28}Si + ^{12}C interaction.

products observed[10] near θ_{cm} = 180° from the ^{28}Si + ^{12}C interaction are plotted in Fig. 3. (Experimental details will be suppressed; these, together with a more complete discussion of the following considerations, may be found in Ref. 10.) It is readily seen from the figure that the elastic cross sections, even though remarkably large for such a large center-of-mass scattering angle, are dwarfed by the combined inelastic and rearrangement yields corresponding to more strongly damped reactions. Furthermore, the average Q-values, <Q>, for a given reaction product were found to remain constant over the entire range of measured angles ($40 \leq \theta_{lab} \leq 20°$ corresponds approximately to $170° \geq \theta_{c.m.} \geq 140°$), as is illustrated for the carbon yields in Fig. 4.

The measured yields were converted to center-of-mass cross sections using the average Q-values (which, again, do not depend on angle in the angular region under investigation), and the resulting angular distributions are plotted in Fig. 5. All rise toward θ_{cm} = 180° with a $1/\sin\theta$ dependence. Angular distributions measured at different incident energies show essentially identical behavior, except for changes in overall cross section magnitude. Thus, these large-angle yields, which exceed the elastic cross section by approximately two orders of magnitude, appear in a variety of two-body exit

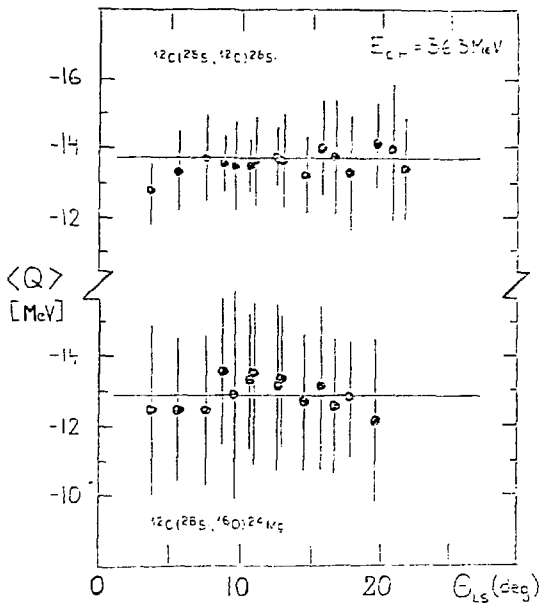

Fig. 4. Average Q-values for C,O yields observed at various angles in the ^{28}Si + ^{12}C interaction.

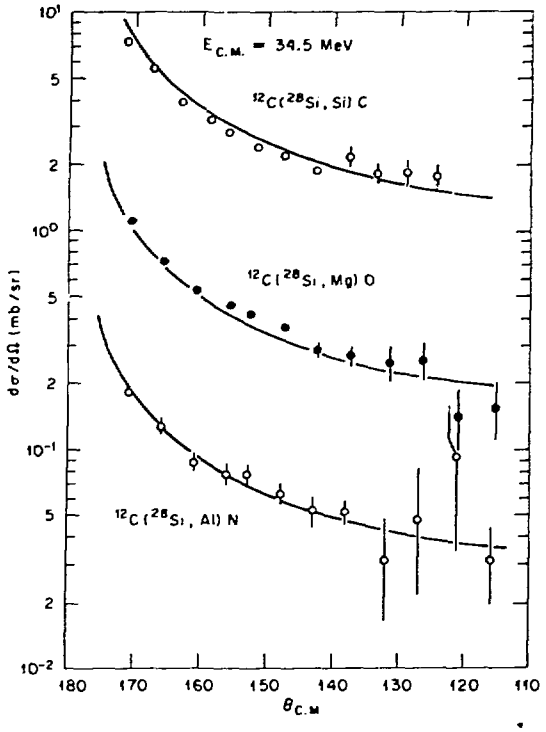

Fig. 5. Angular distributions for the total C, N, and O yields from the ^{28}Si + ^{12}C interaction.

channels, and are strongly damped in energy, are emitted from a long-lived complex formed during the collision.

The bombarding energy dependence of the average Q-values for the various exit channels implies that the long lifetimes can be associated with orbiting. Our measurements, plotted in Fig. 6, show that <Q> increases linearly with beam energy in each case. This behavior is entirely consistent with a simple model in which the total kinetic energy (TKE) is equated with the energy stored in a rotating di-nuclear system:

$$TKE = E_{c.m.} - \langle Q \rangle = V_{Coul}^{(d)} + V_{Nucl}^{(d)} + Q_{g.s.} + \frac{h^2}{2\mu d^2} \ell_f(\ell_f+1).$$

The experimentally determined slopes and intercepts are reproduced with this equation using a proximity potential for V_{Nucl}, the sticking model to relate

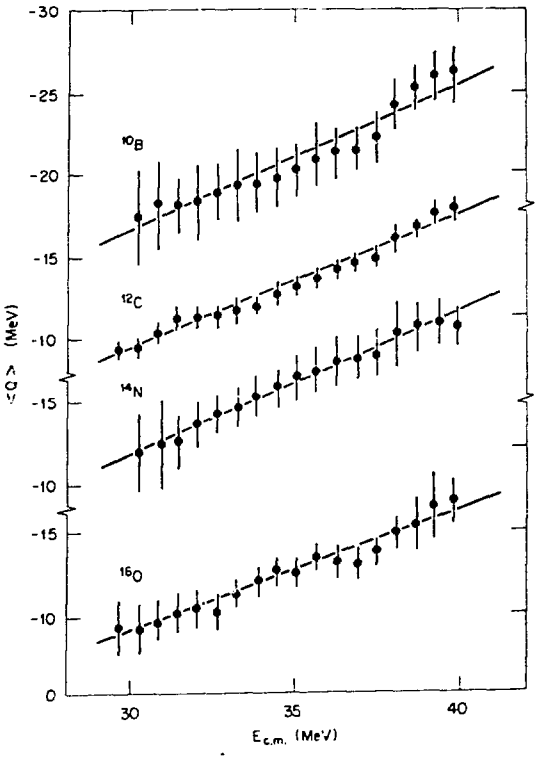

Fig. 6. Bombarding energy dependence of the average Q-values for B, C, N, and O reaction products from the $^{28}Si + ^{12}C$ interaction.

the entrance and exit channel orbital angular momenta (ℓ_i and ℓ_f, respectively), and $\ell_i = (\ell_{gr} + \ell_{cr})/2$ with the grazing and critical ℓ-values respectively determined from elastic[12] and fusion[10] data. Good agreement with the measurements is obtained only when values for the separation coordinate, d, of approximately 7 fm are used, however, showing the peripheral nature of the assumed orbiting mechanism.

Taken together, the above results find a natural interpretation in terms of a rotating di-nuclear molecule. The energy spectra indicate that strong if not complete damping of the energy degree of freedom has occurred, and this perhaps provides appropriate initial conditions for the establishment of a quasi-stable orbiting complex. Clearly, the connection between the back-angle behavior of the $^{28}Si + ^{12}C$ interaction and the deep-inelastic mechanism deserves further investigation. Our findings that $\langle Q \rangle$ and $d\sigma/d\theta = \sin\theta d\sigma/d\Omega$ remain constant beyond $\theta_{c.m.} = 140°$ for each of the boron, carbon, nitrogen, and oxygen exit channels, show that both energy damping and charge and mass transfer precede the evolution of the di-nuclear system toward back angles. These results would appear to rule out any direct connection between the reaction yields at individual backward angles and the corresponding classical impact parameter. Instead, an interpretation involving an initial fast reaction mechanism followed by orbiting would seem more appropriate. It will

be of considerable interest to measure the reaction products over the entire angular range in order to follow the evolution of the system in detail.

The orbiting behavior of a fully developed di-nuclear molecule cannot be described in terms of a single or even just a few partial waves. Thus, resonant structure does not appear in the excitation functions for the total yield. Partial wave summations for individual exit channels that couple to the orbiting complex presumably can be modified by the coupling in an energy-dependent manner, however, leading to resonance-like behavior in such channels. In addition, orbiting reaction amplitudes corresponding to positive and negative angle deflections will be of comparable magnitude near 180°, and their coherent superposition could lead to angular distribution oscillations that depend sensitively on beam energy.

These and many other implications remain to be explored both experimentally and theoretically in the future. Their significance derives from the observation that the cross sections associated with the di-nuclear molecule exhaust at least 25% of the total non-fusion cross section for $^{28}Si + ^{12}C$ collisions at $E_{c.m.} = 40$ MeV. If the mechanisms leading to the formation of an orbiting di-nuclear molecule in the $^{28}Si + ^{12}C$ system are only weakly dependent on the properties of particular channels, as the present data suggest, similar behavior should be a general feature of the collisions of light nuclei.

4. A FIRST LOOK AT $^{60}Ni + ^{60}Ni$ COULOMB BARRIER INTERACTIONS

Resonant structure similar to that found in lighter systems has been discovered recently in $^{28}Si + ^{28}Si$ interactions by Betts, et al.[13] It remains an important open question whether collisions involving even heavier nuclei exhibit similar structure. The presence of resonant behavior in these interactions would open new areas for investigation, while its absence would define more sharply the conditions under which resonances exist and may be observed.

We are currently measuring Ni+Ni elastic and inelastic Coulomb barrier

scattering ($E_{lab} \sim 200$ MeV) in order to investigate these and related questions,[14] using beams from the new Holifield tandem accelerator at Oak Ridge. We do not know yet whether resonances exist in these systems, but preliminary results reveal for the first time some very significant differences from the behavior observed in the scattering of lighter nuclei.

Fusion is by far the dominant reaction process in collisions of light nuclei at energies up to several times the Coulomb barrier. Broad bumps which may or may not reflect resonances appear in these fusion yields as a function of energy, but <u>all</u> quantitative information concerning resonance spins has been derived from studies of elastic and quasi-elastic exit channels. The latter never contain more than a few percent of the total reaction cross section at energies where resonances are observed.

We have found that the distribution of reaction cross section is entirely different for ^{60}Ni + ^{60}Ni collisions near the Coulomb barrier. Our elastic scattering measurements at E_{lab} = 228 MeV are plotted in Fig. 7, while Fig. 8

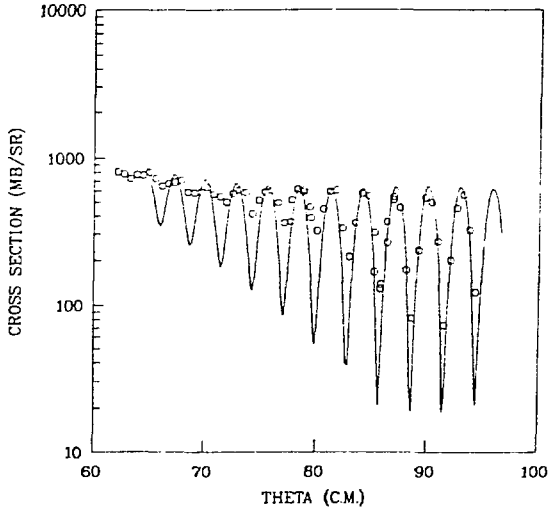

Fig. 7. ^{60}Ni + ^{60}Ni elastic scattering angular distribution at E_{lab} = 228 MeV. The curves are CCBA calculations discussed in the text.

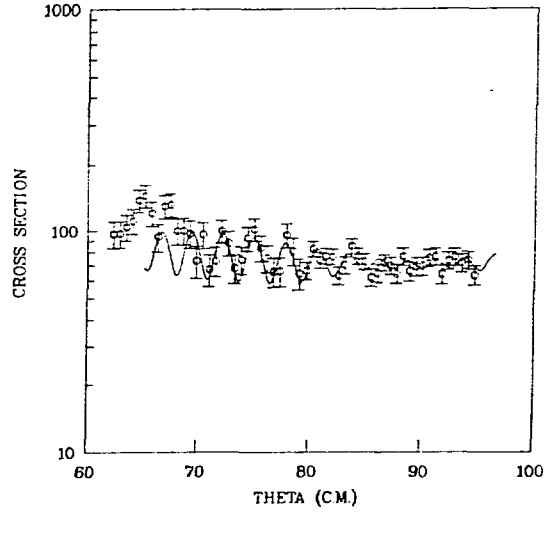

Fig. 8. ^{60}Ni + ^{60}Ni 2^+ inelastic scattering angular distribution at E_{lab} = 228 MeV, in mb/sr. The curves are CCBA calculations described in the text.

shows the corresponding differential cross sections for inelastic excitation of the lowest 2^+ level in either target or projectile. For comparison, the results of preliminary coupled-channels calculations using the code PTOLEMY[15] are also shown. A standard light-ion optical potential (V = 40 MeV, W = 15 MeV, r = 1.20 fm, a = 0.54 fm) was used, together with the previously measured B(E2) value, in these calculations. Comparable agreement between theory and experiment was obtained with these parameters at the other energies measured (E_{lab} = 198 and 176 MeV). The quality of the fits can be improved, but even these first-pass calculations lead to some interesting conclusions.

The total 2^+ inelastic cross section accounts for approximately 95% of the total reaction cross section at the Coulomb barrier energy of E_{lab} = 198 MeV. Variations in optical model parameters lead to variations in this fraction, of course, but only of the order of a few percent. Thus, very little cross section is left over for fusion; the quasi-elastic channels dominate the ^{60}Ni-^{60}Ni interaction at energies near the Coulomb barrier.

Inspection of the coupled-channels results shows that Coulomb excitation is responsible for these very large inelastic yields. As a consequence, this phenomenon will be a characteristic feature of the collisions of heavy symmetric systems in general.

Our observations have several implications -- as yet mostly unexplored -- for resonance studies in heavy systems. On the one hand, the dominance of the quasi-elastic yields and the corresponding very small fusion cross sections suggest that any resonances present will not damp significantly into the compound (fused) system. On the other hand, entrance channel structures will be masked in the elastic and inelastic exit channels by very strong Coulomb excitation. It thus appears that studies of rearrangement channels offer the best hope for the observation of Coulomb barrier resonances in heavy systems, provided the long-range absorption observed in our work does not preclude the formation of resonances altogether. Alternatively, studies at significantly

higher bombarding energies, where the balance between the Coulomb and nuclear interactions will be different, should be undertaken. The new generation of high energy, high resolution accelerators makes such studies possible now.

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