In summary, a clear indication of the effects of the deuteron D state on the polarization of the 2.58-MeV ($\frac{7}{2}^-$) state has been obtained in the ^{58}Ni($p, d\gamma$) angular-correlation measurement at an incident energy of 30 MeV. The importance of the D-state effects to the polarization of the residual nuclear states can be understood by examining the DWBA formalism.

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Selectivity in Two-Particle Exclusive Heavy-Ion Reactions

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A high-resolution study of two-particle exclusive reactions of ^{28}Si + ^{28}Si over a wide range of bombarding energy shows interesting selectivity in both the mass and the energy spectra. The mass spectra display an enhanced population of every fourth mass which gives way to an enhancement of every second mass at the higher energies. The energy spectrum of inelastically scattered particles shows a selective population of mutually excited yrast states in both fragments.

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There have been essentially no previous studies of heavy-ion reactions with projectiles heavier than ^{16}O in which the energy resolution was sufficient to resolve individual final states of the product nuclei.[1] Such experiments are potentially of great interest as they in principle contain significant information on the reaction mechanism through, for example, any selectivity in final-state population. Indications of such selectivity have been reported by Novotny *et al.*,[2] who observed broad structures in the spectrum of inelastically scattered ^{32}S from ^{28}Si. The energy resolution of the experiment precluded, however, any identification of these structures.

In this Letter we present the results of a high-resolution study of two-particle exclusive channels populated in $^{28}Si + ^{28}Si$ reactions over a wide range of bombarding energy. The energy spectra of the emitted fragments show a strong selectivity which is interpreted as arising from a dominance of mutual excitation of yrast states in both fragments. The mass yields show a similarly interesting selectivity. The population of every fourth mass is favored at the intermediate bombarding energies studied, giving way to a selective population of every second mass at the higher bombarding energies. Previous studies[3] of both elastic and inelastic scattering yields for $^{28}Si + ^{28}Si$ show distinct resonance behavior in the energy and angular range studied here. The present results are therefore taken to be typical of orbiting collisions for this system.

The experiment was performed with use of a ^{28}Si beam from the Argonne National Laboratory superconducting linac booster to bombard a target consisting of 25 $\mu g/cm^2$ of Si on a thin C backing. The energies and angles (E_3, θ_3, E_4, and θ_4) of coincident reaction products were measured with two position-sensitive Si surface-barrier detectors. Each detector subtended an angular range of approximately 20°, one at a mean angle of 37° to the beam, the other at 50° on the other side of the beam axis. Data were taken at seven bombarding energies ranging from 85 to 150 MeV. At the lowest energy, the angular range of the measurement encompasses the grazing angle and at the higher energies, angles much larger than the grazing angle.

For a two-body final state, the mass of one of the emitted fragments is given by the relation

$$M_3 = \frac{M_1 E_1 \sin^2\theta_4}{E_3 \sin^2(\theta_3 + \theta_4)}, \tag{1}$$

where M_1 and E_1 are the mass and energy of the beam particles. The mass of the other fragment is given by a similar relation. The measured parameters were therefore used to calculate these masses. The spectrum of $M_{tot} = M_3 + M_4$ thus obtained shows a narrow peak centered at $M_{tot} = 56$ with a width of 1.5 mass units superimposed on a broader peak of width 6 mass units. The former then corresponds to pure two-body final states while the latter includes more complex final states, which only approximately obey two-body kinematics. The relative contributions of the two processes is a strong function of energy, that from multibody final states increasing with increasing bombarding energy. We note, however, that multibody events will not in general give rise to sharp peaks in the mass or energy spectra.

To select two-body final states, a window of width 1 mass unit was set on the peak at $M_{tot} = 56$. The M_4 spectra for these events are shown in Fig. 1 for each of the bombarding energies measured. At the lowest energies, the spectra are uncontaminated by multibody events. At the higher

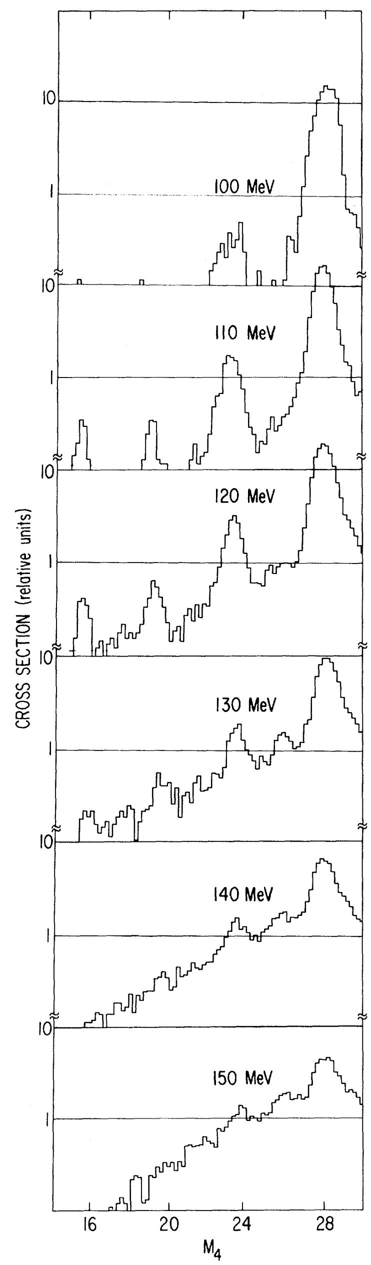

FIG. 1. Mass spectra obtained after requiring $55.5 \leqslant M_{tot} \leqslant 56.5$. The 85-MeV spectrum, which is not shown, displays only a peak at $M_4 = 28$.

energies, events arising from multibody final states are responsible for a smooth background on top of which are the peaks due to two-body events. These mass spectra show some interesting features. Reactions with no net transfer of particles dominate at all energies over reactions in which particles are transferred. For such transfer reactions there is a pronounced selectivity in the final masses populated. At the intermediate bombarding energies, every fourth mass is enhanced, a feature which gives way to an enhancement of every second mass at the higher bombarding energies. We emphasize here that these yields represent transitions to bound states of the product nuclei and that the observation of, for example, mass 16 implies a two-body final state—one with mass 16, the other with mass 40; both in particle-stable states.

At first sight, the population of every fourth mass at the intermediate bombarding energies would seem to reflect the ground-state Q values ($Q_{g.s.}$) for α-particle and multiple-α-particle transfer, which are considerably less negative than those for other mass transfers. This dependence can be obtained from a consideration of the phase space in each reaction channel which, crudely, should depend on $Q_{opt} - Q_{g.s.}$, where Q_{opt} is the optimum Q value. The dependence of Q_{opt} on mass is a smooth one and the mass dependence of the yields is therefore expected to be largely determined by $Q_{g.s.}$. The favoring of every second mass observed at the higher bombarding energies is, however, not accounted for by such an argument, the Q values for pair-exchange reactions being quite similar to those in which an odd number of nucleons are exchanged. The implication is then either that the structure of the orbiting intermediate complex favors such mass splits or that the mass yields are determined by the behavior of some potential-energy surface other than the asymptotic one as is, for example, the case in fission. Such a change with increasing bombarding energy is then clearly an important feature of the data to be reproduced by any theory of mass fragmentation in heavy-ion reactions. We further note that the present data clearly show that it is possible to transfer large amounts of mass without large energy loss which would necessarily leave the resulting fragments in particle-unstable states. This is not to say that the observed correlation[4] between average energy loss and average number of particle transfers does not exist but rather that the fluctuations about these averages may be as large as the effect itself.

Further interesting features appear in the energy spectra of the emitted particles. Mass-28 events were selected and total energy ($E_{tot} = E_3 + E_4$) spectra generated. Rather than using the measured energies to do this, the values of E_3 and E_4 were obtained from the angular measurements by setting M_3 and M_4 identically equal to 28 for these events and rearranging Eq. (1) so as to

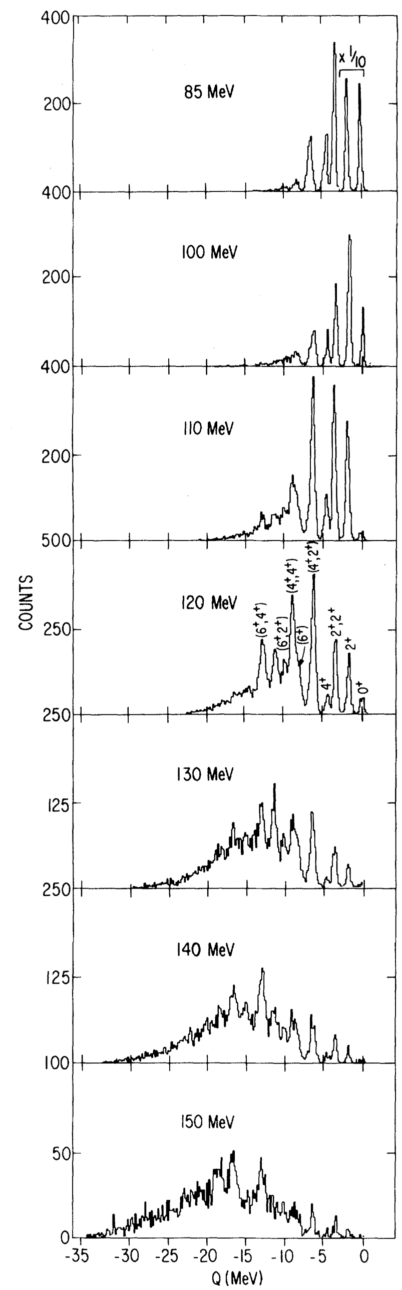

FIG. 2. Energy spectra for $M_4 = 28$ events obtained as described in the text. The peak assignments are indicated on the 120-MeV spectrum.

solve for the energy. In addition to superior energy resolution (300 keV full width at half maximum versus 1 MeV from the energy measurement) the peak shapes do not seem to be subject to the low-energy tails observed in the energy-measured spectra.

Energy spectra obtained in the above manner are shown in Fig. 2 for each bombarding energy. In addition to peaks corresponding to elastic scattering and inelastic scattering to low-lying states of ^{28}Si, strong peaks are observed at much more negative Q values with widths consistent with those of single states. Using the peaks unambiguously identified as elastic scattering, single and mutual excitation of the 1.78-MeV 2^+ state, and single excitation of the 4.62-MeV 4^+ state as calibration points,[5] we are then able to make some rather definite statements regarding the identifications of the other peaks in these spectra. In particular, the strong peak immediately above the 4.62-MeV 4^+ excitation is identified as due mainly to a mutual excitation of the 1.78-MeV 2^+ and 4.62-MeV 4^+ states. Identifications of the higher-lying peaks are more speculative but the locations of these peaks are consistent with their arising from mutual excitation of yrast states in both fragments, as indicated in Fig. 2. One particularly interesting feature of these spectra is the almost complete absence at the higher bombarding energies of a peak corresponding to the 6.88-MeV collective 3^- state in ^{28}Si. For energies above 100 MeV, a peak at this Q value appears only as a small shoulder on the $(4^+, 2^+)$ peak. This dominance of multiple excitation of yrast states in the inelastic spectra most likely signifies the close connection between energy loss and angular momentum transfer resulting from angular-momentum–matching conditions between the entrance and exit channels. Estimates of the optimum angular-momentum transfer as a function of Q value, based on a knowledge of the grazing angular momentum as a function of energy, do indeed account for the observed selectivity if the spins of the mutually excited fragments are aligned parallel to each other. This has been suggested[6,7] to occur in much lighter systems and is also implicit in friction models[4] of inelastic heavy-ion collisions. The importance of angular momentum effects in the reaction mechanism for these heavy-ion collisions then suggests that this may also be a useful way of exciting nuclei to high-spin yrast states and that there should be significant effects on the reaction mechanism depending on the collective properties of the participating nuclei.

In summary, a high-resolution study of the mass and energy spectra in the collision of ^{28}Si + ^{28}Si shows a high degree of selectivity. It is likely that further studies of this type will not only illuminate some of the features of heavy-ion reaction mechanisms but may also prove useful in the study of the structure of the colliding nuclei themselves.

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