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Intermediate Structure Resonances in ^{56}Ni

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Detailed excitation functions of angle-integrated cross sections for ^{28}Si + ^{28}Si elastic scattering and reactions show narrow, highly correlated structures. These resonances have enhanced partial widths for decay into two ^{28}Si fragments and are interpreted as having quasimolecular or fission-isomeric nature.

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The intense interest in the intermediate width structure ($\Gamma_{c.m.} \sim 100$ keV) observed in excitation functions for some heavy-ion reactions stems from the belief that this signifies the existence of highly clustered or moleculelike doorway states in the composite system.[1] For the ^{12}C + ^{12}C and ^{12}C + ^{16}O systems, at energies not too far above the Coulomb barrier, extensive experimental studies have demonstrated the nonstatistical origins of the observed structure and strongly support an interpretation as a true resonance phenomenon.[2-6] For these systems at higher energies[7,8] and for heavier systems,[9-12] the situation is less clear. Structure of width comparable to that seen in much lighter systems has been observed. In most cases, however, the data are insufficient to distinguish between a resonance or statistical origin of the observed structures.[13] The connection between these heavier systems and the ^{12}C + ^{12}C and ^{12}C + ^{16}O systems therefore remains to be made. The possibility that this connection exists is an exciting one, as it would signify the observation of nuclear structure effects at higher excitation energies and larger angular momentum than previously directly accessible, the understanding of which will provide important tests of our understanding of nuclear behavior.

In this Letter we present the results of detailed excitation-function measurements for $^{28}Si + ^{28}Si$ reactions over a range of bombarding energies in the vicinity of twice the Coulomb barrier. Angle-integrated yields for elastic scattering and reaction channels show a series of broad ($\Gamma_{c.m.} \sim 2.5$ MeV) structures, each of which is fragmented into peaks of width ~150 keV. The narrow peaks appear in a highly correlated fashion in essentially all channels measured as well as in the total yield summed over all channels. These data, together with the results of previous elastic scattering angular distribution measurements,[14] favor an interpretation in terms of a number of very-high-spin ($J \sim 40\hbar$) doorway states at excitation energies of up to 70 MeV in the composite system.

The experiment was performed with use of a ^{28}Si beam from the Brookhaven National Laboratory tandem accelerator to bombard a 7-μg/cm^2 ($\Delta E = 70$ keV) ^{28}Si target mounted on a 20-μg/cm^2 C backing placed with the ^{28}Si toward the beam. Coincident fragments were detected in two large-area (600 mm^2) surface-barrier detectors placed on either side of the beam axis. The defining detector covered the angular range 33.5°–47.5° in the horizontal plane with a solid angle of 60 msr. The recoil detector subtended a 2° larger range both in and out of plane. The coincidence efficiency of this arrangement is 100% for elastic scattering and decreases almost linearly to zero for $Q = -20$ MeV. Data were taken in 100-keV steps from 105 to 121 MeV bombarding energy. The data were normalized to both the integrated beam current and to the elastic scattering yield in a fixed monitor detector. Some twenty repeat points taken throughout the experiment verified the accuracy of this procedure.

A spectrum obtained at a bombarding energy of 110 MeV is shown in Fig. 1. The identifications of the resolved peaks are based on the results of previous[15] high-resolution study, and are indicated in the figure. The normalized angle-integrated yields for these transitions as well as the total yield are shown in Fig. 2, plotted as a function of $E_{c.m.}$. The data are characterized by two distinct types of structure. We observe three broad ($\Gamma_{c.m.} \sim 2.5$ MeV) structures, in good agreement with the results of an earlier experiment[14] with a much thicker target and larger energy steps. Each of these broad structures is fragmented into several much narrower peaks with widths $\Gamma_{c.m.} \sim 150$ keV and spacings of a few hundred keV. The strong correlation between

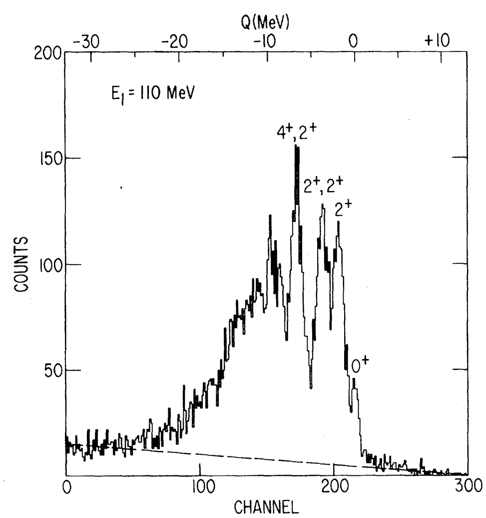

FIG. 1. Total-energy spectrum of coincident fragments obtained at a bombarding energy of 110 MeV. The identifications of the resolved peaks are from Ref. 15. The dashed line indicates a linear background which was subtracted from the yields.

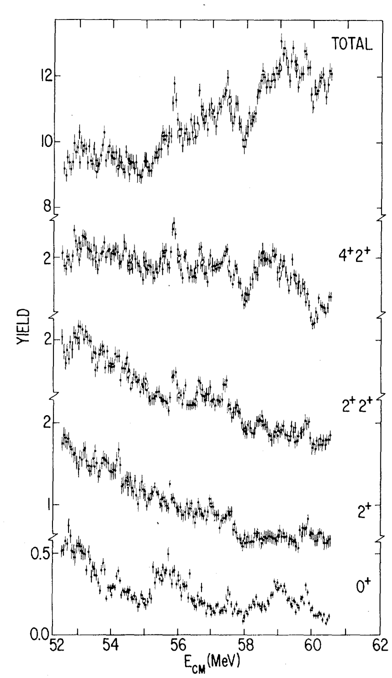

FIG. 2. Angle-integrated yields of the elastic scattering, 2^+, mutual 2^+, and mutual $(4^+, 2^+)$ excitations shown as a function of $E_{c.m.}$. The top part of the figure shows the total yield in the spectrum.

these narrow peaks in the various channels is immediately obvious—a feature which indicates a nonstatistical origin. This is accentuated by the appearance of the same narrow peaks in the total cross section, despite the averaging over many channels implicit in this quantity. We note here the qualitative similarity between the behavior of the total cross section in the present data and the features of evaporation residue cross sections for lighter systems.[16]

In order to place these observations on a more quantitative footing, the data were subject to a correlation analysis. Data for the four resolved transitions as well as the yield in the remainder of the spectrum were used to calculate the summed, normalized deviation function $D(E)$ and the normalized cross-correlation function $C(E)$:

$$D(E) = \sum_{i=1}^{5} D_i(E),$$

$$C(E) = \frac{1}{10} \sum_{i>j=1}^{5} D_i(E) D_j(E),$$

with

$$D_i(E) = \left(\frac{\sigma_i(E)}{\langle \sigma_i(E)\rangle} - 1\right)\left(\frac{\langle \sigma_i^2(E)\rangle}{\langle \sigma_i(E)\rangle^2} - 1\right)^{-1/2}.$$

The results of this procedure are shown in Fig. 3. The averaging interval used was 2 MeV (laboratory). Large positive values of $D(E)$ indicate correlated maxima, negative values correlated minima. For $C(E)$, the expectation for uncorrelated data is a distribution of values centered about zero. This is clearly not the case for the present data, which show a considerable excess of large positive values of $C(E)$. In order to gauge the significance of these results, the expected errors on $D(E)$ and $C(E)$, based on the finite averaging interval and the statistical errors in the data itself were calculated. With the above definitions of $D(E)$ and $C(E)$ we find standard deviations of $\pm\sqrt{5}$ and approximately ± 0.10, respectively; these are indicated as the shaded regions in Fig. 3. Most of the narrow structures observed in the data appear with values of $D(E)$ and $C(E)$ well outside the shaded regions. For the energy-averaged value of $C(E)$ we find $\langle C(E)\rangle = 0.18$ which is to be compared with the expected value[17] of 0.0 ± 0.04 for statistical fluctuations. We may therefore conclude with some confidence that the narrow structures observed in the data do not arise from statistical Ericson fluctuations and must therefore be ascribed to true resonances.

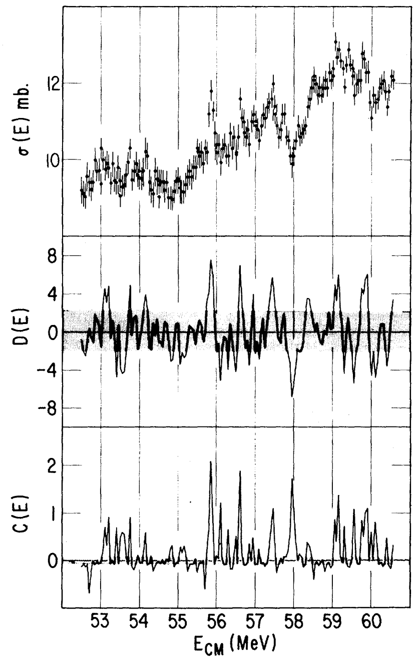

FIG. 3. The total cross section (top); the summed, normalized deviation function $D(E)$ (center); and the normalized cross-correlation function $C(E)$ (bottom). The shaded regions indicate the expected standard deviations of the $D(E)$ and $C(E)$ distributions for uncorrelated data (with 68% confidence).

It is likely that the narrow resonances have extremely high spin. Elastic-scattering angular distributions[14] indicate angular momenta of $36\hbar$, $38\hbar$, and $40\hbar$ for the three broad structures observed in the present data, the angular distribution shapes remaining essentially constant over each structure. In order to gain some understanding of these resonances we consider the properties of the compound nucleus at these angular momenta and the appropriate excitation energies. In view of the lack of knowledge of nuclear level densities at such high excitation energies and angular momenta, estimates of this quantity are necessarily uncertain. Calculations of the level density with use of a back-shifted Fermi-gas density formula[18] with standard parameters and a moment of inertia from the rotating-liquid-drop model[19] give values ranging from 10^5 MeV^{-1} for $J = 36\hbar$, $E_x = 64$ MeV to 5×10^3 MeV^{-1} for $J = 40\hbar$, $E_x = 70$ MeV. These compound-nuclear level densities lead to values of a few eV for the partial width for decay of the average compound level into two ^{28}Si nuclei in their ground states. Experimentally, a resonance analysis of the elastic-scattering cross sections and the total yields in terms of isolated resonances incoherently superimposed on a nonresonant background give values of a few keV for the elastic partial width—orders of magnitude larger than the above estimate for statistical decay. As is the case for $^{12}C + ^{12}C$, we are therefore faced with the existence of narrow resonances in a region of high level density which apparently have a strong structural connection with the symmetric entrance channel, implying an extremely deformed or "quasimolecular" nature.

Most theoretical interpretations of the resonances[20-22] in lighter systems have utilized a molecular basis comprised of these states generated by the rotations of a dinuclear molecule coupled to intrinsic excitations of the nuclei themselves. The more complex nature of the low-lying spectrum of ^{28}Si provides a somewhat greater density of such molecular states. In principle, however, there is no reason that this approach should not be able to describe the present data. Another interesting possibility, especially in view of the current interest in the structure of nuclei at high angular momentum, is based on the results of calculations of nuclear shell structure and equilibrium shapes as a function of deformation.[23] These calculations indicate the occurrence of shell gaps at large deformations which lead to secondary minima in the potential energy surfaces. These secondary minima can give rise to semistable, shape-isomeric states. At low angular momentum, the large fission barrier prevents such shape isomers from fissioning. At large angular momentum, however, where the only decay mode of the nucleus is fission, it may be proper to term these states fission isomers.[24] Such isomers may be expected to manifest themselves in the fashion observed in the present data. One qualitative expectation based on this suggestion is the sensitivity of this phenomenon to the neutron or proton number of the compound nucleus. Based on the calculations of Ref. 23 we expect the narrow structure to disappear with increasing neutron number although the broad structures may remain.

In summary, detailed excitation-function measurements yielding angle-integrated cross sections for many channels demonstrate the resonance origin of the structures observed in $^{28}Si + ^{28}Si$ reactions. The resonances display enhanced partial widths for decay into symmetric channels which suggests their interpretation as extremely high-spin quasimolecular states in analogy to those previously observed in much lighter systems. An alternative description in terms of high-spin fissioning shape isomers is also suggested.

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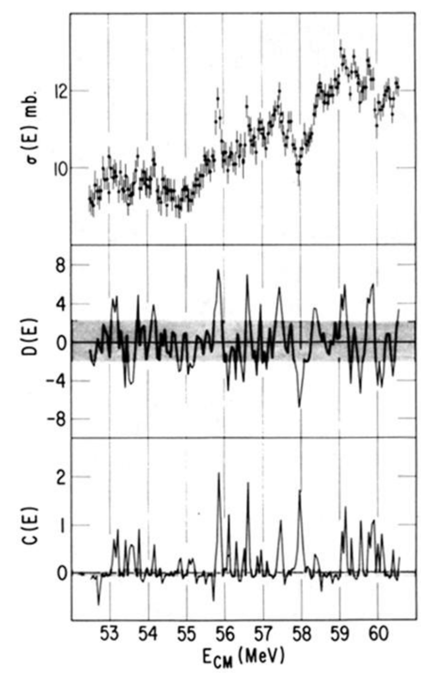

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