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HIGH-ANGULAR-MOMENTUM RESONANCES IN ^{28}Si + ^{28}Si SCATTERING*

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The initial expectation was that resonance behavior in heavy-ion systems would be limited to only a few special systems and to energies not too far above the Coulomb barrier. The past few years have shown us that this behavior has a much wider extent than was previously thought possible, although in many cases the indications of resonance behavior is at best qualitative. In this talk I will present results for the ^{28}Si + ^{28}Si system - the heaviest in which resonance behavior has yet been observed.

Initial measurements[1] of ^{28}Si + ^{28}Si elastic scattering angular distributions (Fig. 1) show little evidence for the surface transparency required for resonance behavior. The angular distributions

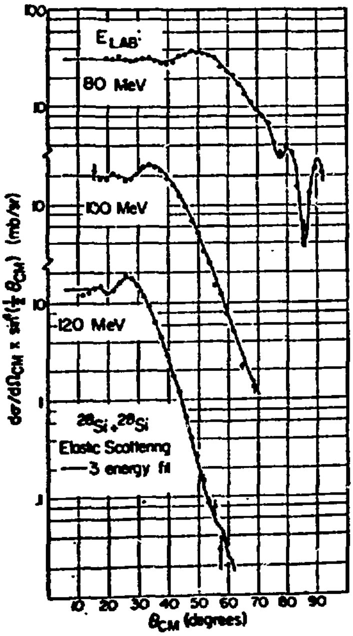

FIGURE 1.

show a Fresnel type diffraction pattern, characteristic of strong absorption. Measurements at large angles[2] and at cross-section levels of about 10^{-4} of the Coulomb cross-section, however, show distinct resonance-like behavior. Elastic scattering cross-sections measured at two angles over a range of energies in the vicinity of twice the Coulomb barrier are shown in Fig. 2. These data do not show the regular behavior observed in lighter symmetric systems but seem to display both structures of width several MeV and indications of much narrower structure, although the step size of 1 MeV (lab) makes the distinction rather difficult. Similar behavior is seen in channels other than the elastic scattering channel as shown in Fig. 3. Of particular interest here is the nature of these inelastic channels. Initially it was thought that a peak observed near 6.5 MeV in the spectrum corresponded to the excitation of the collective 6.89 MeV 3^- state in ^{28}Si. A high resolution study[3] has shown that this initial supposition is incorrect and that this peak corresponds to a mutual excitation of the 1.78 MeV 2^+ and 4.62 MeV 4^+ levels which then appears at an apparent excitation energy of 6.40 MeV. In fact, for these energies and for this angular range, the inelastic scattering spectrum of ^{28}Si + ^{28}Si is dominated by mutual excitations of yrast levels as

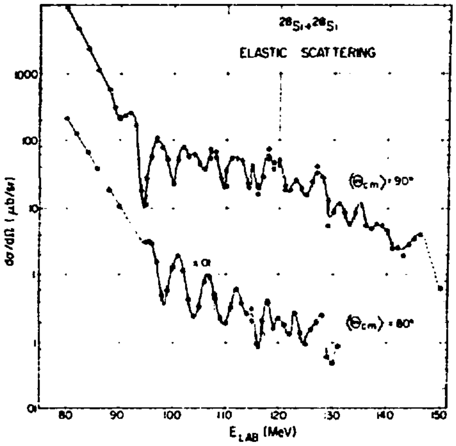

FIGURE 2.

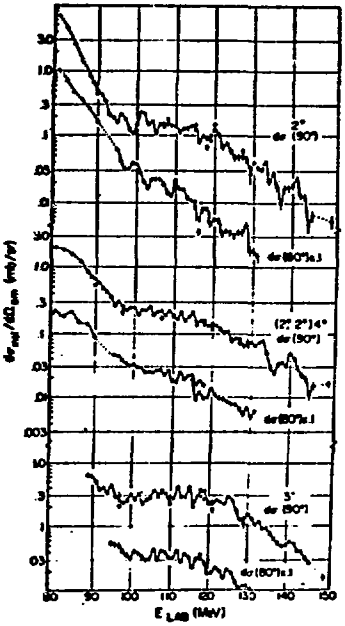

FIGURE 3.

shown in Fig. 4 - a result which can be understood qualitatively in terms of angular momentum matching if the spins of the mutually excited fragments are aligned parallel to one another.

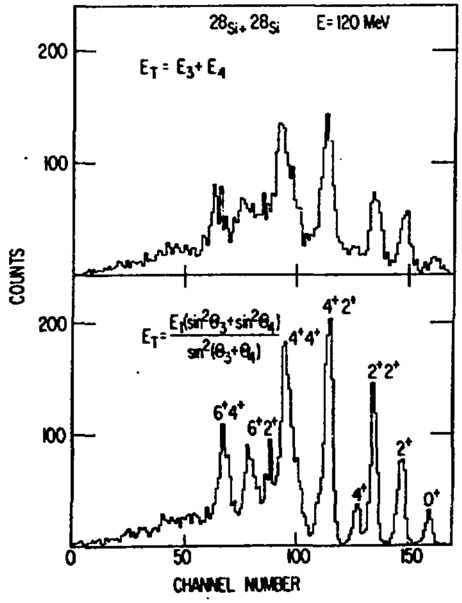

FIGURE 4.

The structures observed in the single angle excitation functions persist when the cross-sections are integrated over a reltively large angular range,[4] $\Theta_{CM} \approx 60°-90°$, as shown in Fig. 5, and also appear in the angle integrated yield summed over all final channels with $Q \geqslant -10$ MeV.

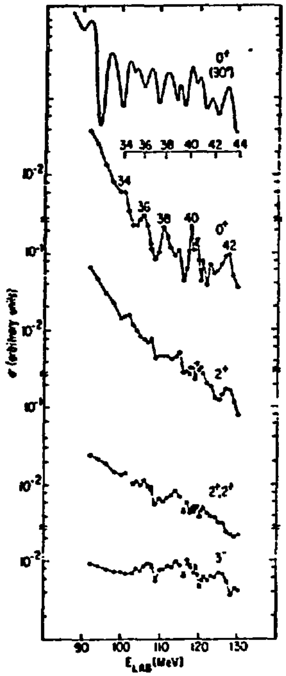

FIGURE 5.

The elastic scattering angular distributions[4] have shapes characterized by single Legendre polynomials squared for each of the broad structures observed in the angle integrated elastic scattering cross-sections. These are shown in Fig. 6. The values of L associated with these Legendre polynomials follow the grazing partial wave rather closely as indicated in Fig. 5. Only in the deep minima between the broad structures do we observe angular distributions not characterized by a single L although the shapes of these are still highly oscillatory.

The appearance of a definite narrow structure near 118 MeV as shown in Fig. 5 led us to a further investigation in which angle integrated cross-sections for elastic and inelastic scattering were measured single 2^+, mutual 2^+, mutual 4^+2^+ and the rest of the yield in the spectrum as well as the total yield in the spectrum were extracted. Comparison of repeat points taken during the experiment indicate that the errors associated with these yields are less than 5% with the exception of the elastic scattering channel which has poorer statistics and an error of 10%. These yields are shown in Fig. 8. The data are in good agreement with our previous results taken in 1 MeV steps but the finer energy steps reveal a much richer structure than was evident in the earlier data. Structures of width 100-200 keV appear throughout the data for the individual channels as well as in the total yield for the whole spectrum. There appears to be a strong correlation between many of the narrow structures, a feature which is not expected for structures arising from statistical fluctuations.

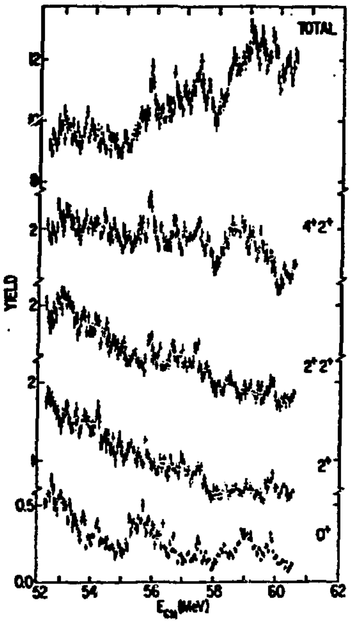

FIGURE 8.

To put the observed correlations on a quantitative footing we have performed a correlation analysis of the data and compared the results with the expectations for uncorrelated data. As the question of confidence limits on the results of correlation analysis is not well documented, the main features of our analysis are outlined here.

The experimental cross-sections σ were used to generate an average cross-section $<\sigma>$ using a Gaussian smoothing function with FWHM = 1500 keV. These quantities were then used to generate

$$y_i = \frac{\sigma_i}{<\sigma_i>}$$

where now the broad ($\Gamma \sim 2$ MeV) structures have been removed by the averaging procedure. In principle, the distribution of y can then be compared with the theoretical expectation P(y) based on statistical fluctuations. P(y) is, however, a function of two variables N, the number of channels, and y_D the non-fluctuating or "direct" contribution to the cross-section. N is given by geometrical constraints and may be considered fairly well known but y_D is in general undetermined except by comparison with the experimental results through the relation

$$C(0) = \frac{1}{N_{eff}} = \frac{1}{N}\,(1 - y_D^2)$$

where C(0) is given by the normalized variance of the data.

$$C_i(0) = \frac{<\sigma_i^2>}{<\sigma_i>^2} - 1$$

Comparison of the experimental distribution of y with the theoretical expectation is therefore not particularly useful as the latter then has the experimental results factored in. We therefore introduce a new variable

$$X_i = \frac{y_i - <y_i>}{\sqrt{<y_i^2> - <y_i>^2}}$$

where the average is now over the entire range of data. Both experimentally and theoretically X_i are normally distributed with variance unity. For the summed deviation function and normalized cross-correlation

$$D(E) = \frac{1}{N} \sum_{i=1}^{N} x_i$$

$$C(E) = \frac{2}{N(N-1)} \sum_{i>j=1}^{N} x_i x_j$$

and for uncorrelated data we therefore expect D(E) and C(E) to have distributions with mean zero and standard deviations $\frac{1}{\sqrt{N}}$ and $\sqrt{\frac{2}{N(N-1)}}$ respectively. The former of these results is trivial, the latter is approximate but accurate, the exact result requiring numerical integrations. The experimental values for D(E) and C(E) are shown in Fig. 9 together with the expected standard deviations of the theoretical

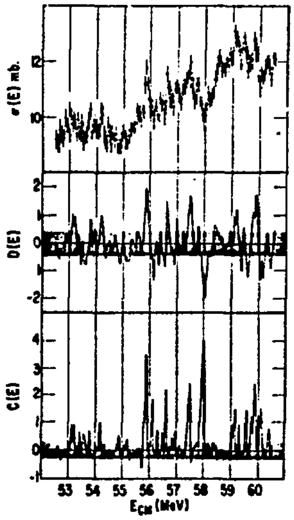

FIGURE 9.

distributions (shaded areas). Most of the narrow structures appear with values of D(E) and C(E) several standard deviations away from zero. The experimental and theoretical frequency distributions are shown in Fig. 10 - the probability that these experimental distributions result from uncorrelated fluctuations is in both cases less than 1 part in 10^5.

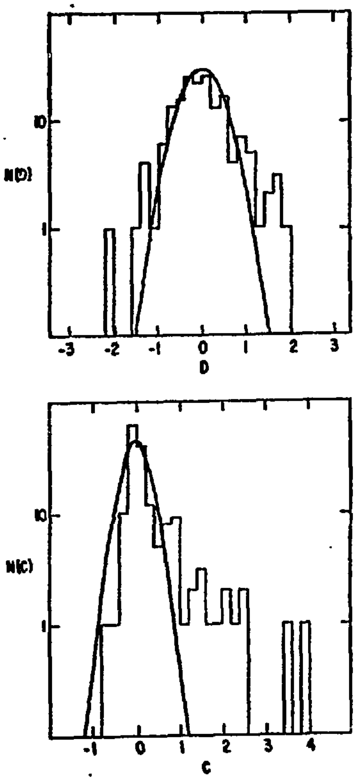

FIGURE 10.

Finally, the energy averaged value of C(E) is expected to be

$$\langle C(E)\rangle = 0.0 \pm \sqrt{\frac{2}{N(N-1)}} \quad \sqrt{\frac{\pi\Gamma}{\Delta}} \quad = 0.0 \pm .04$$

where $\Delta/\pi\Gamma$ is the number of independent cross-sections (Γ = coherence width, Δ = energy range of the data). This is to be compared with the experimental value of $\langle C(E)\rangle = 0.27$. We therefore conclude that the narrow structures observed in the data do not arise from statistical fluctuations and thus must be ascribed in true intermediate structure resonances.

On the basis of all the above we conclude that we are dealing with a number of narrow resonances with extremely high angular momentum - of order 40 ħ. If we consider the compound nucleus at these excitation energies and angular momenta using, for example, the rotating liquid drop model to estimate the position of the yrast line, we find level densities which are still several thousand per MeV. This implies a partial width for the average compound nuclear level to decay into the ^{28}Si + ^{28}Si elastic channel of a few eV whereas from the experimental results we estimate values of a few keV. As is the case with the much lighter systems, 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.

An interpretation in terms of models which utilize a "quasi-molecular" basis is not implausible. Fig. 11 shows the spectrum of

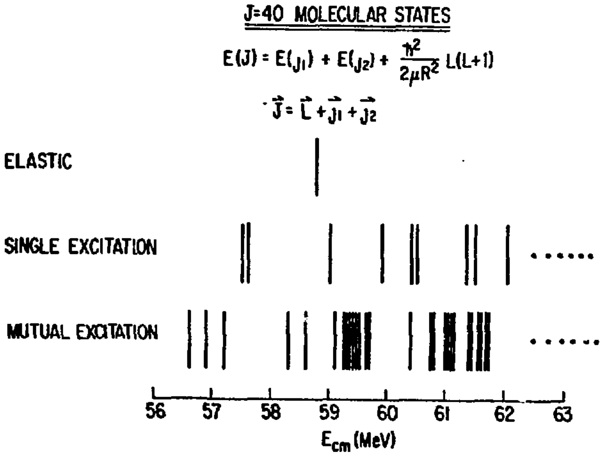

FIGURE 11.

J=40 molecular levels formed by coupling of the excitations of the individual nuclei to the rotations of the dinuclear system with a center-to-center radius equal to the strong absorption radius. The number of such states within the observed width of the gross structures is certainly not inconsistent with the experimental observations. The question of how these basis states are mixed and the value of the background absorption reflecting mixing with more complex excitations are however open ones.

Another interesting speculation is based on the results of calculations of shell structure as a function of deformation and angular momentum for the nucleus ^{56}Ni - the compound nucleus for $^{28}Si + ^{28}Si$. These calculations[6] indicate the occurrence of a second minimum at large deformations for a limited range of angular momenta in the vicinity of J=40. Such a second minimum can give rise to shape isomeric states which are expected to decay largely by fission. The connection between these calculations and the present experimental results is tenuous at best, although such fissioning shape isomers may be expected to manifest themselves in the manner observed.

To investigate this possibility we have performed an experiment in which we attempt to observe these resonances by populating the composite system via the $^{16}O + ^{40}Ca$ entrance channel and looking for decays into $^{28}Si + ^{28}Si$. The experiment was performed using a kinematic coincidence arrangement similar to that of Ref. 3 in which the energies and angles of coincident fragments were used to obtain mass identification via two-body kinematics. A mass spectrum obtained at a bombarding energy of 75 MeV is shown in Fig. 12 - the yield of symmetric events is surprisingly large and corresponds to an angle integrated cross-section of several mb. This yield was measured in 250 keV steps over the bombarding energy range 72 to 78 MeV - the target thickness was comparable to the step size. The yield of symmetric events is shown plotted as a function of ^{56}Ni excitation energy in Fig. 13 and is compared with the total yield from the $^{28}Si + ^{28}Si$ entrance channel which is shown as the solid curve. The $^{28}Si + ^{28}Si$ data have been averaged so as to correspond to the

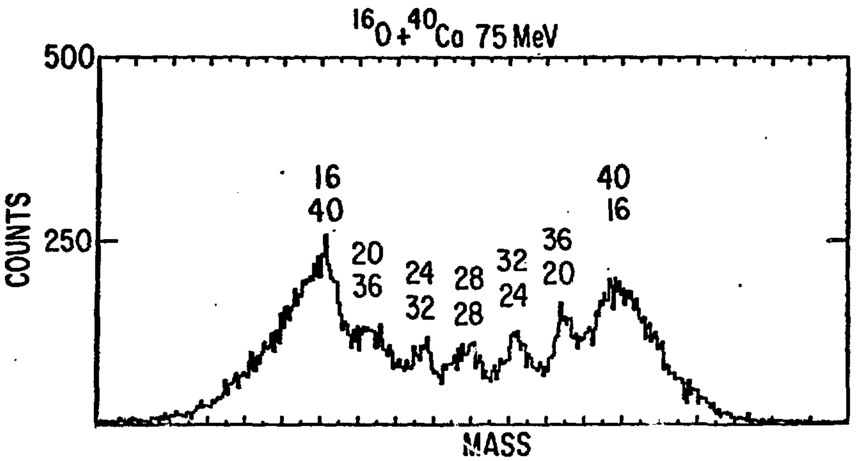

FIGURE 12.

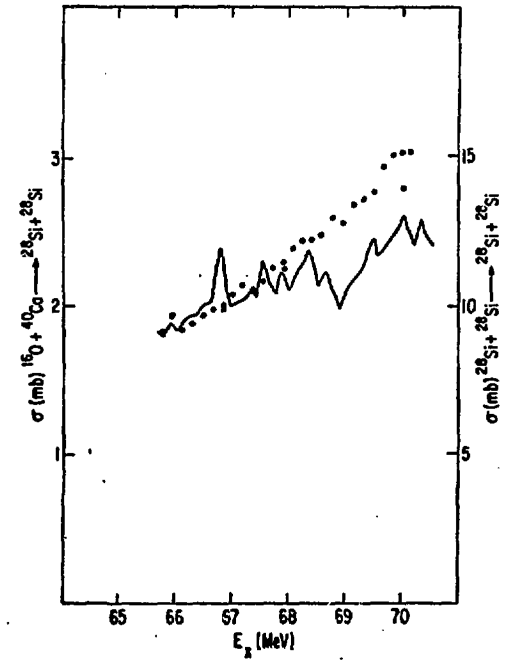

FIGURE 13.

same target thickness as for the $^{16}O + ^{40}Ca$ experiment. The $^{16}O + ^{40}Ca$ data are quite smooth showing none of the prominent structures observed in the $^{28}Si + ^{28}Si$ entrance channel data. The grazing angular momenta for the two entrance channels differ by only 1 $\hbar$ for the same excitation energy and these data would therefore tend to suggest that the observed structures in the $^{28}Si + ^{28}Si$ reactions be described in terms of entrance channel degrees of freedom.

Finally, we address the extent to which resonance phenomena may appear in even heavier systems of which the $^{40}Ca + ^{40}Ca$ system has been considered to be the most likely to show such behavior. Data for the elastic scattering of ^{40}Ca on ^{40}Ca are shown as a function of energy in Fig. 14. These data represent the average differential cross-section over the center-of-mass angular range 77-103°. The solid

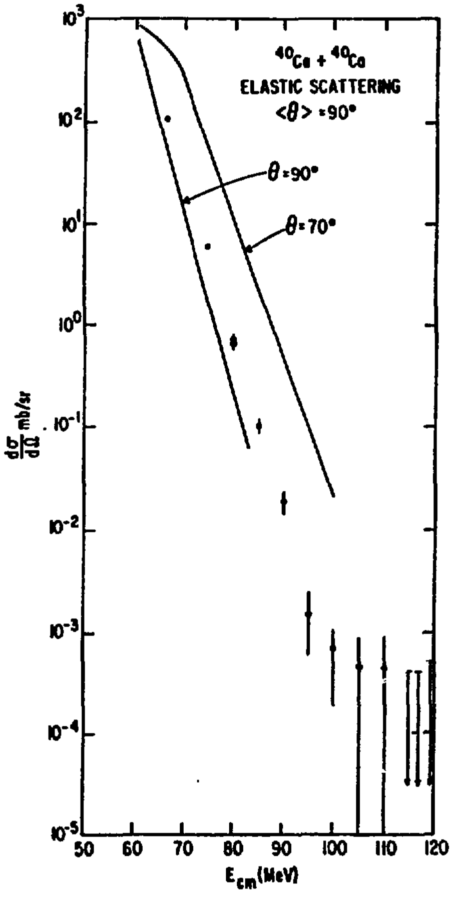

FIGURE 14.

lines show the results of an earlier study by an Orsay group.[7] The cross-sections fall smoothly down to a level of 0.5 μb/sr $(\frac{\sigma}{\sigma_{Coul}} \approx 10^{-6})$ with no hint of any leveling which might be characteristic of resonance behavior. We have also measured the total quasi-elastic and deep inelastic cross-sections for $^{40}Ca + {}^{40}Ca$ in 1 MeV (lab) steps from 170 to 195 MeV. A preliminary analysis of these data indicate no structure at the 3% level and our tentative conclusion is that $^{40}Ca + {}^{40}Ca$ does *not* show resonance behavior.

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