Resonant Fluctuations in Heavy-Ion Reaction Cross Sections: $^{16}O(^{16}O,\alpha)^{28}Si$

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Synthetic small-angle excitation functions and angular distributions are calculated for the reaction $^{16}O(^{16}O,\alpha_0)^{28}Si$ by use of a compound-nucleus decay model which includes angular momentum conservation. Fluctuations in the synthesized cross sections are shown to exhibit all the general characteristics of measured α_0 cross sections, including features usually attributed to resonances.

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The systematic study of resonant phenomena in heavy-ion reactions has been pursued as a method to examine nuclear structure in compound systems at high excitation energies and angular momenta which are not available via light-ion interactions. This method achieves nuclear-structure significance only where it is possible to reliably determine that each resonance is an emission of flux from a special compound state which is essentially isolated in energy. Insofar as the structures observed in heavy-ion reactions at energies just above the Coulomb barrier are similar in width, $\Gamma \sim 100-500$ keV, and amplitude to the structure predicted by statistical models of nuclear reactions, it is uncertain whether the observed anomalies are isolated resonances or merely cross-section fluctuations resulting from the statistical decay of overlapping compound states. Because of the random nature of fluctuations, statistical models of nuclear reactions cannot predict the cross section at a particular energy. They do, however, predict the average properties of cross sections. The identification of isolated resonances in the presence of statistical fluctuations requires a comparison of the predicted properties of fluctuating cross sections about their averages with the properties of experimental data.

Resonance criteria based on the average properties of fluctuations are utilized in several recent studies[1-3] of intermediate width structure in the cross sections for the $^{16}O(^{16}O,\alpha_{0,1})^{28}Si^*$ reactions leading to the residual 0^+ ground state and 2^+ first excited state. "Resonances" in these reaction channels at $E_{\text{c.m.}} \sim 15.2$, 15.8, 15.9, and 16.1 MeV have been reported from the combined works of Gai *et al.*[1] and Liendo, Gay, and Fletcher.[2] With use of a partial-wave analysis[1] or a Legendre analysis[2] of their angular distribution data, they have made spin assignments for these resonance energies of 10^+, 10^+, 8^+, and 8^+, respectively. Their resonance interpretations are based largely on the persistence of these structures in α_0 and/or α_1 cross sections which have been summed over angular intervals which are substantially larger than the statistical coherence angle.[4]

The purpose of this Letter is to examine the properties of fluctuations in the $^{16}O(^{16}O,\alpha_0)$ reaction cross section in order to determine whether the observed resonant structures are consistent with statistical-model predictions. A method for synthesizing fluctuating cross sections with a computer model,[5] which includes angular momentum conservation, is used to generate a number of $^{16}O(^{16}O,\alpha_0)$ excitation functions and angular distributions in the energy range from $E_{\text{c.m.}} = 12$ to 20 MeV. Realistic spin-dependent level densities for the compound nucleus and the decay nuclei are incorporated in the model. Comparisons are made of the characteristics of the structures in the synthesized-to-measured[2,6] α_0 cross sections. The synthesized fluctuations are found to exhibit all the general features of the α_0 data, including resonant structure, where a single partial wave resonates near the maximum of a fluctuation, which appears in the angle-integrated cross section as well as in the differential cross section. The appearance in data of structure with these characteristics has been considered previously to be evidence of isolated resonances.[1,2]

Details of the formalism used to synthesize the fluctuating $^{16}O(^{16}O,\alpha_0)$ cross section are given in a previous publication.[5] Briefly, the interference from the population and decay of overlapping compound-nucleus levels is included explicitly in the differential cross section

$$\frac{d\sigma_{\alpha'\alpha}}{d\Omega}(\theta,E) \propto \sum_{J_1,J_2} \mathrm{Re}[S^{J_1}_{c'c}(E)^* S^{J_2}_{c'c}(E)], \qquad (1)$$

where

$$S^J_{c'c} = \exp[i(\eta^J_{c'} + \eta^J_c)] \sum_v \frac{i g^J_{c'v} g^J_{cv}}{E^J_v - E - i(\Gamma/2)}. \qquad (2)$$

In Eq. (2), E^J_v and Γ^J_v are respectively the energy and total decay width of the compound-nucleus level v, E is the compound-nucleus excitation energy of the reaction, η^J_c is the Coulomb-plus-nuclear potential phase shift in channel c, and g^J_{cv} denotes the reduced width amplitude for decay level v into channel c multiplied by the appropriate kinematical factor. The population of the compound-nucleus levels from the entrance channel is modeled by assigning to each level a value for the amplitude g^J_{cv}, which is selected randomly from a Gaussian distribution of zero mean and a width that is deduced from the relation

$$\{(g_{c\nu}^J)^2\} = (T_c^J \Gamma^J)/G^J, \tag{3}$$

where T_c^J is the optical-model transmission coefficient, Γ^J is the average decay width for levels of spin J, and G^J is the sum over the transmission coefficients of all energetically open decay channels. The curly brackets denote averaging over compound-nucleus levels. The value for the amplitude $g_{c'\nu}^J$ for decay of the level into the exit channel is assigned, independent of the entrance channel amplitude, via random selection from a Gaussian distribution of zero mean and a width deduced from Eq. (3) with use of a transmission coefficient $T_{c'}^J$ appropriate to the exit channel.

The relation expressed in Eq. (3) incorporates the statistical-model assumptions that all compound-nucleus levels of a given spin are populated equally, on the average, and the decay to a particular final state is determined by its statistical weight among the open decay channels. For some heavy-ion reactions, the variation with total angular momentum J of the entrance-channel flux and the number of open decay channels restricts significant fluctuation amplitudes to a narrow range of spins centered near the grazing angular momentum in the entrance channel.[4,5] Hauser-Feshbach calculations[7] of energy-averaged $^{16}O(^{16}O,\alpha_0)$ partial cross sections versus J show the FWHM to be <3 units of angular momentum wide over the region of 12 to 20 MeV with significant contributions from $J=8$, 10, and 12 in the neighborhood of $E_{c.m.}=16$ MeV.[8]

The strong localization of the $^{16}O(^{16}O,\alpha_0)$ partial cross sections permits a simplified synthesis of fluctuations. The sums over the compound-nucleus levels implicit in Eq. (1) are restricted to encompass a maximum of three sequential even values of total angular momentum. Specifically, amplitudes for levels with $J=8$, 10, and 12 are summed coherently in the calculations at energies from 13.4 to 16.3 MeV. Amplitudes are summed for levels with $J=6$, 8, and 10 at energies below 13.4 MeV and with $J=10$, 12, and 14 at energies above 16.3 MeV. The energies of levels in $^{32}S^*$ are found by use of a Fermi-gas-model level density formula[9] with the level density parameter of Vandenbosch and Lazzarini[10] to obtain the average spacing D^J for states of spin J. The energies of the levels are chosen randomly within $\pm D^J/2$ of the Fermi-gas-model predictions of their positions. Small contributions to the cross section from levels not included explicitly are approximated by the Hauser-Feshbach cross section[7] for the appropriate spin.

No adjustments of parameters are necessary to generate the density and magnitude of the fluctuations in the synthetic $^{16}O(^{16}O,\alpha_0)$ excitation functions, one of which is compared with a measured excitation function[2,6] in Fig. 1. The density of fluctuations in the synthetic excitation function is determined by the total decay width Γ_ν^J of the compound-nucleus levels. In the present calculations, $\Gamma_\nu^J=130$ keV for all levels which is the value obtained for $^{32}S^*$ at a mean excitation $E\sim32.5$ MeV ($E_{c.m.}\sim16$ MeV) from a semiempirical evaluation of experimentally deduced average decay widths.[11] Open particle decay channels leading to the eight pairs of residual nuclei with the largest ground-state separation energies are accounted for in the simulations. Level densities for the residuals are obtained by use of the method described in Ref. 9. Transmission coefficients T_c^J for the open decay channels are determined by use of the optical-model potential of Greenwood *et al.*[12] in addition to those utilized by Pocanic *et al.*[3] in $^{16}O(^{16}O,\alpha)$ Hauser-Feshbach calculations.[7] The above calculations are sufficient to fix the breadth of the Gaussian distributions from which the entrance and exit channel amplitudes are chosen randomly for each of the compound-nucleus levels.

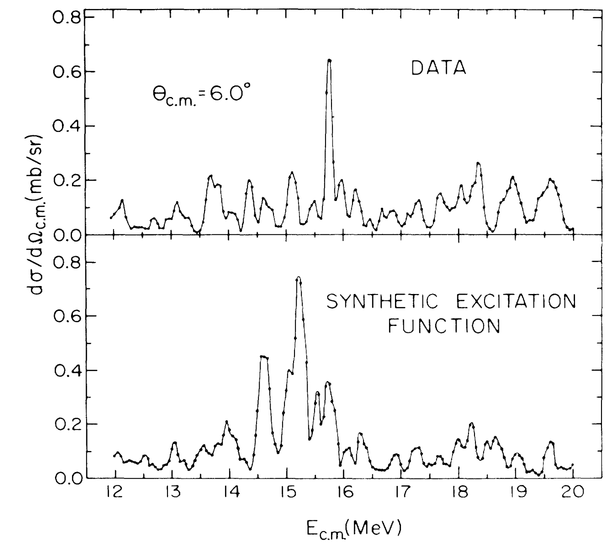

FIG. 1. A comparison of $^{16}O(^{16}O,\alpha_0)^{28}Si$ small-angle excitation functions: measured (from Refs. 2 and 6) and synthesized with use of a statistical-model formalism which includes coherent contributions from compound-nucleus levels within a restricted range of angular momenta.

The results of a second calculation are shown in Fig. 2. In this calculation, the contributing compound-nucleus levels have amplitudes in the entrance channel that are unchanged from the previous calculation, but different amplitudes in the exit channel have been assigned via random selection as described following Eq. (2) above. Although the energy dependence of the small-angle cross section seen in Fig. 2(a) exhibits no systematic correlation to that seen in the synthetic excitation function of Fig. 1, the density of narrow structures generated by the two calculations is virtually the same.

The total synthetic cross section for the α_0 channel is plotted versus energy in Fig. 2(b). Many of the narrow,

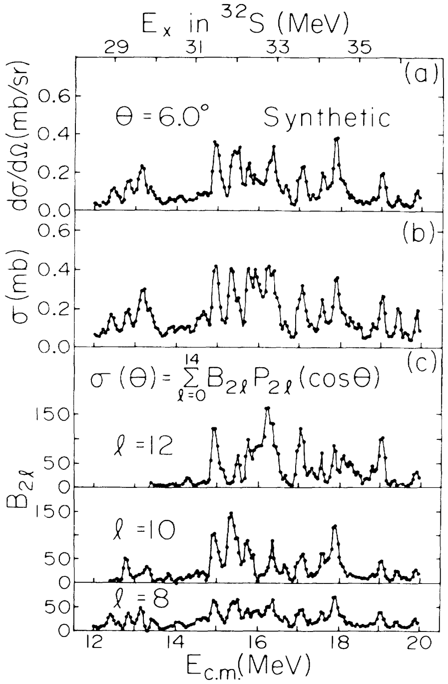

FIG. 2. Synthetic cross sections of the $^{16}O(^{16}O,\alpha_0)^{28}Si$ reaction: (a) Excitation function of α_0 differential cross section at $\theta_{c.m.}=6°$; (b) excitation function of the total α_0 cross section; (c) Legendre coefficients B_{2l} for $l=8$, 10, and 12 obtained in least-squares fits to the synthetic α_0 angular distributions.

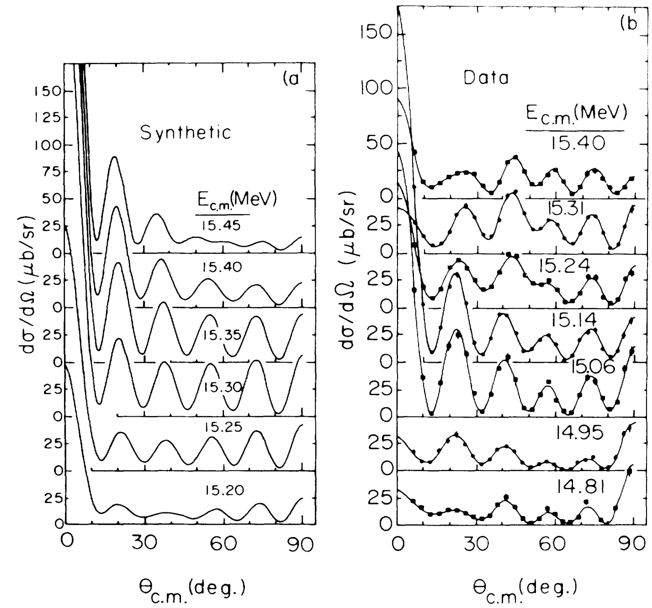

FIG. 3. Comparison of resonant features observed in synthetic α_0 angular distributions: (a) with those in measured α_0 angular distributions and (b) taken from Ref. 6.

resonancelike structures evident in the small-angle cross sections of Fig. 2(a) persist in the total cross sections. Some of the structures in the total α_0 cross section occur at energies which are shifted slightly from the positions of their counterparts in the small-angle cross section. The shift in peak positions is less than the total decay width $\Gamma=130$ keV of the underlying compound-nucleus levels and can be attributed to the interference of amplitudes for levels with different spins which is present in the differential, but not in the total, α_0 cross section.

In the study of heavy-ion resonances, it is customary to examine the angular momentum characteristics of such resonant structures as are evident in Fig. 2(b). Recent investigations in the $^{16}O(^{16}O,\alpha_0)$ reaction channel have employed different analyses of angular distribution data to extract resonant J^π values.[1-3] The linear Legendre method[13] has been utilized by Liendo, Gay, and Fletcher[2] and is applied for the same purpose to the synthetic cross sections. Evaluations of the unique coefficients in the linear expansion,

$$\sigma(\theta,E)=\sum_{l=0}^{L=14} B_{2l}(E)P_{2l}(\cos\theta),$$

are performed in least-squares fits to the synthetic α_0 angular distributions. Resonant spins are inferred from the energy dependence of the Legendre coefficients $B_{2l}(E)$ for $l=8$, 10, and 12 in the region $E_{c.m.}\leq 16.3$ MeV where the maximum contributing angular momentum is $J=12$. The energy dependence of the evaluated coefficients shown in Fig. 2(c) reveals an interesting feature of the fluctuating cross section. Structures in the $B_{2l}(E)$ curves for $l=8$ and $l=10$ show that the resonancelike maxima in the total α_0 cross section at $E_{c.m.}\sim 12.4$ MeV and ~ 13.2 MeV are predominantly $J^\pi=8^+$, whereas the intermediate maximum at ~ 12.4 MeV is predominantly $J^\pi=10^+$. Similarly, a strong $J^\pi=10^+$ structure appears at ~ 15.3 MeV between maxima at ~ 14.9 and 15.7 MeV where the $J^\pi=12^+$ component prevails. These results make evident the statistical likelihood of finding resonant fluctuations that are dominated by one particular spin amidst other resonant fluctuations which are predominantly of a different spin. Resonant spin mixing among fluctuations is an important feature of the synthetic cross sections considering the presence of similar groups of structures in $^{16}O(^{16}O,\alpha)$ data.[1,2]

Figure 3(a) shows several synthetic α_0 angular distribution curves. The $J^\pi=10^+$ character of this structure is clearly evident in the shape of the angular distributions near the maximum of the total cross section, but not near the energies of the adjacent minima. The energy-dependent character of these synthetic angular distributions is highly reminiscent of the changes in the shapes of the measured α_0 angular distributions taken from Ref. 6 and shown in Fig. 3(b). The cross sections in Fig. 3 occur in a region where the calculated density of compound-nucleus levels is $\rho_8 \sim 330$/MeV for $J=8$, $\rho_{10} \sim 100$/MeV for $J=10$, and $\rho_{12} \sim 20$/MeV for $J=12$. In this case, the coherent contributions of many $J=8$, 10, and 12 levels generate a resonant structure with a "unique $J=10$" behavior. The appearance of structure in angle-integrated cross sections which is correlated with a dominant resonating partial cross section is a characteristic common to fluctuations and isolated resonances.

With statistical fluctuations exhibiting the general features of resonances in the $^{16}O(^{16}O,\alpha_0)$ reaction channel, methods of discerning isolated resonances amidst fluctuations are limited. Statistical tests are essential to distinguish resonant structures in data where correlations between different exit channels at the resonant energies deviate significantly from the random behavior predicted for fluctuations. We have applied the statistical distribution of maxima test[14] to $^{16}O + {}^{16}O$ reaction cross sections measured simultaneously at small angles for the exit channels α_0, α_1, $^8Be_0$, and $^8Be_1$ for $E_{c.m.} \sim 12$ to 20 MeV.[6] The applied statistical test shows very clearly that the energy correlations between the four exit channels follow a random distribution and there is a low probability for isolated resonances in the energy range covered. The distribution of maxima test and the resonant features of the synthesized fluctuating cross sections leads one to the conclusion that the narrow, resonant structures found in these reaction channels have a statistical-fluctuation origin.

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