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Intermediate resonances in the range of excitation energy from 13.706 to 15.756 MeV in ^{30}P through the ^{28}Si(d, p)^{29}Si reaction

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10 intermediate resonances with their spins and parities were identified in this study. The average width is 160 ± 60 keV, which is consistent with the value 153 keV predicted by Hsu's relationship.

[NUCLEAR REACTION ^{28}Si(d,p), E = 2.0–4.2 MeV; measured $\sigma(E;\theta)$; θ = 15–165°, $\Delta\theta$ = 15°; channel correlation analysis; discussed intermediate structure.]

Large fluctuations in nuclear cross sections have been observed for many reactions at high excitations where the ratio of average compound nucleus width to average compound nucleus spacing, $\langle\Gamma\rangle/\langle D\rangle$, is larger than unity. Such data have been extensively analyzed in terms of the Ericson fluctuation theory.[1] Block and Feshbach[2] and Kerman, Rodberg, and Young[3] have suggested that some of the structure might be due to particularly simple modes of excitation of the nucleus, e.g., two-particle, one-hole (2p1h) states. These states would have unique angular momentum and parity and would have widths which are intermediate between those of the states of the compound nucleus and those of the states of single-particle resonances.

Cross sections[4] for the ^{28}Si(d, p)^{29}Si reaction were measured and analyzed with the Ericson fluctuation theory at our laboratory in the range of deuteron energy from E_d = 2.0 to 4.2 MeV, which corresponds to a range of excitation energy from 13.706 to 15.756 MeV in ^{30}P. From the cross sections,[4] we determined the correlations between the resonances of different excitation functions for decaying channel and angle. The correlations $C_{p_3,p_2}=0.174$ and $C_{p_3,p_4}=0.203$, particularly, between the excitation functions of p_2, p_3, and p_4 are not a result of the random fluctuation as discussed by Ericson.[1] Figure 1 shows a set of typical differential cross sections obtained from numerical averaging over various intervals of the data of Ref. 4 for p_2 at $\theta_{\rm lab}=15°$, and the cross section averaged numerically over a 100 keV interval for p_3 at $\theta_{\rm lab}=15°$, and also for p_2 and p_4 at $\theta_{\rm lab}=30°$. In the figure, the correlations between the resonances in the different excitation functions for decaying channel and angle can be observed. Figure 2 shows the angular distributions around the resonance at E_d = 2.12 MeV. The angular distributions vary smoothly as the energy is changed within the energy range covered by the resonance. The resonances might therefore be the intermediate resonances because (1) there are correlations between the different reaction channels and (2) the angular distributions vary smoothly as the energy is changed within the energy range covered by the resonance. The spins and parities of the resonances observed in the experiment can be determined by fitting the angular distributions averaged over a range of 100 keV with a Legendre polynomial expansion[5]

$$\frac{d\sigma}{d\Omega}=\sum_{n=0}^{\infty} a_n P_n(\cos\theta)\,.$$

As the deuteron energy is low, the expansions include terms through $n=6$. From the energy dependence of the coefficients, the contributions of the outgoing protons with different angular momenta l_p can be obtained. Figure 3 shows the coefficients a_n (E_d) pertinent to the group p_2. In the figure, at E_d = 2.12 and 2.36 MeV, one can observe the peaks in the a_0 plot and no structure in other plots. This kind of character indicates that only $l_p=0$ contributes to the outgoing protons. One also can find peaks at E_d = 2.88 MeV in the a_0, a_1, a_2, and a_3 plots, and the flat or zero values at the same energy of E_d in the other plots; this behavior implies $l_p=1$ contributes to the outgoing protons. The peaks in the a_1 and a_3 plots show that there are interferences between odd and even values, 1 and 2, of l_p. The effect of $l_p=2$ comes from the tail of the peak at E_d = 3.00 MeV in the a_4 plot, because the peak is so close to the peak at E_d = 2.88 MeV. Similar arguments

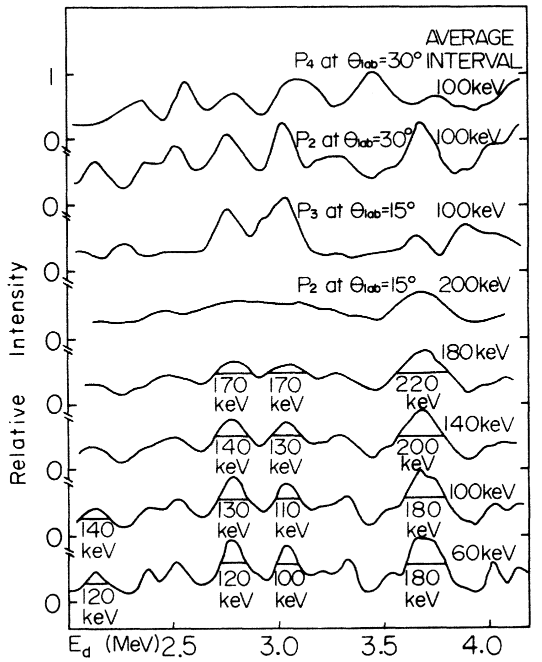

FIG. 1. A set of typical excitation functions of the differential cross sections obtained from various kinds of numerical averaging of the data of Ref. 4. The top four curves are obtained from the data of p_4, p_2, p_3, and p_2 at 30, 30, 15, and 15°, respectively. The bottom four curves are obtained from the data of p_2 at 15°.

are applied to all the peaks. Finally, we conclude that the angular momenta l_p at E_d are as follows: $l_p=0$ at 2.12 and 2.36 MeV; $l_p=1$ at 2.88, 3.28, 3.44, 3.60, and 3.84 MeV; $l_p=2$ at 3.00 MeV; and $l_p=3$ at 2.52 and 2.80 MeV. Thus the resonances at 2.12 and 2.36 MeV (2^+ or 3^+), at 2.88, 3.28, 3.44, 3.60, and 3.84 MeV (4^-, 3^-, 2^-, or 1^-), at 3.00 MeV ($<4^+$), and at 2.52 and 2.80 MeV ($<4^-$) can be concluded because the spin-parity of the second excited state of ^{29}Si is $\frac{5}{2}^+$.

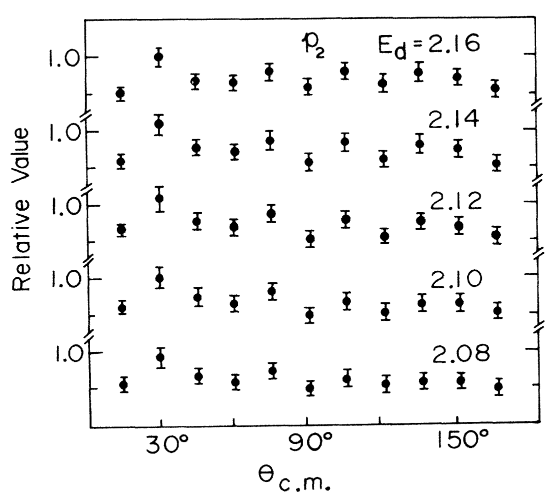

FIG. 2. The angular distributions averaged over 100 keV of p_2 are obtained around the resonance at $E_d=2.12$ MeV.

In Fig. 1, one can also observe that the width of the intermediate resonances have a mean value of 160 keV (± 60 keV). This value is quite consistent with the value $\langle\Gamma_d\uparrow\rangle\approx 153$ keV obtained by Hsu's relation[6]

$$\langle\Gamma_d\uparrow\rangle\approx N_d C_{cc'}{}^2\pi\langle\Gamma_\mu\rangle^2/(n)_{expt}{}^2D\,,$$

with $N_d=2$, $(n)_{expt}=5$, $\langle\Gamma_\mu\rangle=29$ keV, $D=1.38$ keV of our work,[4] and $C_{cc'}=1$ for a single doorway resonance. In the above relation, $N_d=[\frac{1}{2}n_d(n_d-1)]_{expt}$ is the number of combinations of correlated channels, which is the channel correlation coefficient beyond the finite range data error if the coefficient is averaged over the angles and whole experimental energy range. $(n)_{expt}$ is the number of decaying

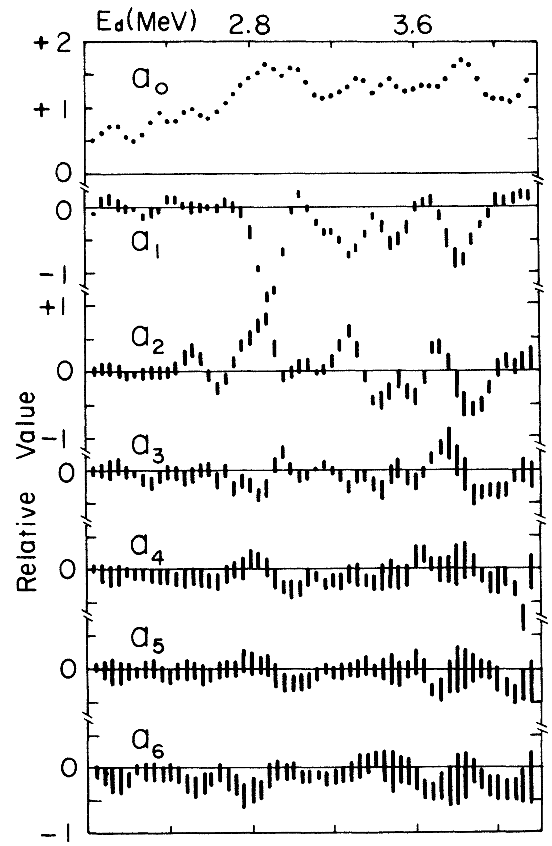

FIG. 3. The coefficients a_n of the Legendre polynomial expansion of the ^{28}Si$(d,p_2)^{29}$Si angular distribution averaged over 100 keV intervals as functions of deuteron energy in steps of 40 keV. The errors are calculated using the method of Rose which appeared in Phys. Rev. 91, 610 (1953).

channels measured in the experiment, and $\langle\Gamma_d\rangle$, $\langle\Gamma_\mu\rangle$, D, and $C_{cc'}$ are the escape width of the doorway resonance, average total level width, average level spacing, and channel correlation at the resonance, respectively. For the width of the intermediate resonance, the consistency between the experimental result and the value predicted by Hsu's relation is very good. The value of $\langle\Gamma_d\uparrow\rangle$, however, is affected so sensitively by N_d that more experiments are needed to confirm the relation.

In the present study of intermediate resonances, 10 resonances with their spins and parities were found. Their locations are at excitation energies higher than 13.706 MeV in ^{30}P. Thus, it is difficult to relate these resonances with the analog states of ^{30}Si without having more information about the levels at excitation energies higher than 13.028 MeV in ^{30}Si.

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