[12] P. D. Ingalls, thesis, Princeton University, 1971 (unpublished).

[13] P. D. Ingalls and G. T. Garvey, to be published.

[14] S. Cohen and D. Kurath, Nucl. Phys. A101, 1 (1967).

[15] Of course the (d,d') experiment does not fix the sign of β. The sign is, however, determined from the value of $\langle H_{CD}\rangle$ calculated using the mass differences cited in the next to last paragraph of this Letter. This result is to be expected on physical grounds and, as is the case for ^{8}Be (Refs. 1–3), the neutron pickup strength tends to increase in the upper level as this configuration has the higher Coulomb energy.

Doorway States and Background Cross Sections in ^{29}Si (γ, n)†

H. E. Jackson and R. E. Toohey*
Argonne National Laboratory, Argonne, Illinois 60439
(Received 24 May 1972)

A study of the reaction ^{29}Si(γ,n) near threshold suggests that a doorway state with $J^\pi=\frac{3}{2}^-$ common to the channels ^{28}Si$+n$ and ^{29}Si$+\gamma$ lies near 750 keV. We observe experimentally Lane's prediction of a significant nonresonant background cross section associated with strong partial-width correlations.

Evidence for doorway states[1] which influence radiative excitation and decay of highly excited nuclear states has been based in large part on the observation of nonstatistical effects in the resonance structure of the radiative cross sections. Recent experimental efforts[2,3] have focused on observation of resonance structure in two reaction channels leading to formation of the same compound states. The objective in these studies has been to observe in each reaction local concentrations of strength that correspond to excitation of the same intermediate states, and further to establish a correlation between the partial widths of these states. Such correlation effects can be interpreted in terms of a doorway state "common" to both channels.

As evidence for a common doorway state in ^{29}Si, this note reports the localization of resonance strength in the reaction ^{29}Si$+\gamma\to{}^{29}$Si* at the same excitation as proposed by Newson[4] for a neutron doorway in the reaction ^{28}Si$+n$, and an almost complete correlation between the partial widths for the corresponding resonances in the two reaction channels. At the same time we wish to present evidence for a third anomaly which can be attributed to the presence of a common doorway state, namely, the presence of a strong background cross section which produces a pronounced interference asymmetry in the shape of a resonance in the (γ,n) reaction at 761 keV. Lane[5] recently predicted such a nonresonant cross section as a direct consequence of the existence of strong correlations in partial widths.

The data were obtained from high-resolution studies of the photoneutron cross section near threshold for ^{29}Si. The measurements were performed at the threshold photoneutron facility[6] at the Argonne high-current electron linac. A 63-g sample of SiO_2 enriched to 95% ^{29}Si was irradiated by a pulsed bremsstrahlung beam with the end-point energy adjusted so that the nuclear states excited by photon absorption could decay by neutron emission only via a transition to the ground state of ^{28}Si. Neutron resonance groups corresponding to each of the states excited were observed by time-of-flight measurements, with the array of neutron detectors set to observe neutrons emitted at 90° and 135° relative to the photon beam. Data taken at 90° with a proton-recoil detector are shown in Fig. 1. A measurement of the photoneutron spectrum with ^{6}Li-glass neutron detectors covering the energy range 5–400 keV revealed only one additional weakly excited resonance level at 60 keV. Extensive data on the total neutron cross section of ^{28}Si are available from the measurements of Schwartz, Schrack, and Heaton.[7] A comparison of the corresponding resonance energies, corrected for recoil effects in the photon and neutron channels, gave agreement for all neutron groups observed in the (γ,n) reaction. One striking feature of the photoneutron spectrum is the sharp interference asymmetries observed in the shapes of resonances at 761 and 530 keV.

We attempted to assign spins of the strong neutron groups by studying the angular distribution of the photoneutrons. Dipole absorption by the $\frac{1}{2}^+$ ground state of ^{29}Si excites $\frac{1}{2}$ and $\frac{3}{2}$ states which then decay by neutron emission to the 0^+ ground state of ^{28}Si. For the spin sequence $\frac{1}{2}-\frac{1}{2}-0$, the

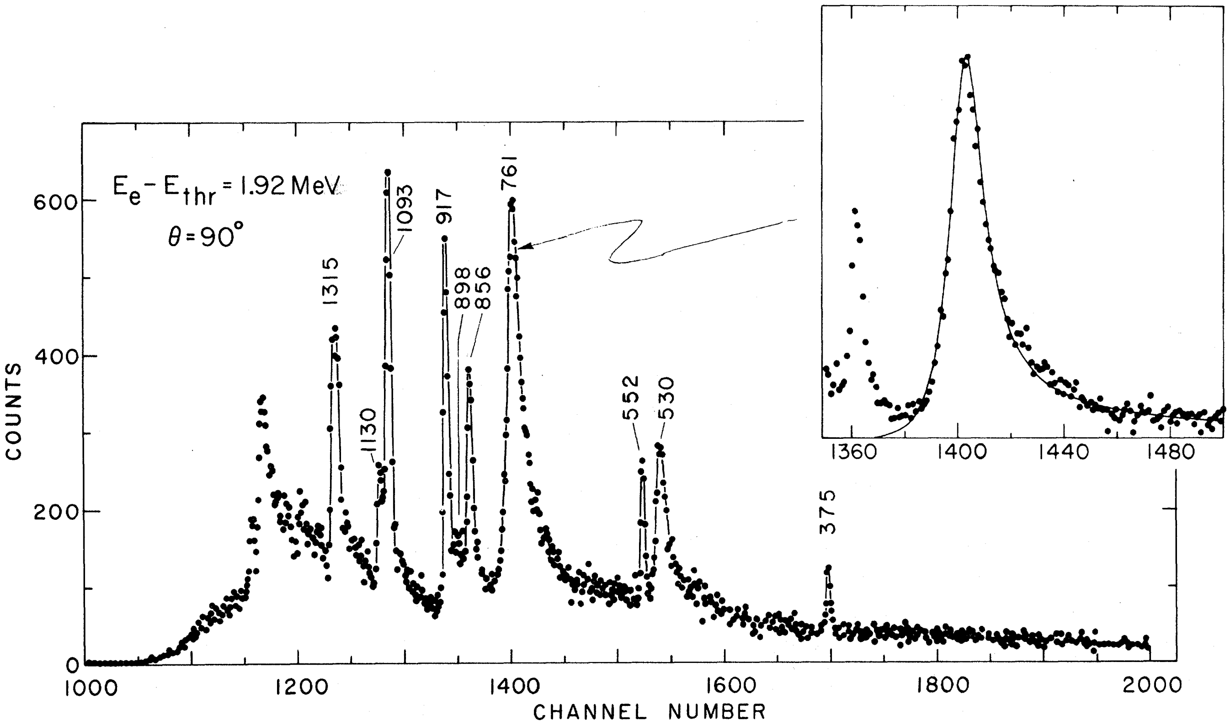

FIG. 1. Photoneutron time-of-flight spectrum for ^{29}Si(γ, n). Flight path, 9 m; bremsstrahlung pulse width, 6 nsec; pulse repetition rate, 800 pulses/sec; average linac current, ~25 μA. The spectrum was accumulated in a 24-h run. The data have not been corrected for variations in detector efficiency or for the energy dependence of the incident flux. Resonance energies are given in keV. Inset, expanded plot of the data in the region of the 761-keV resonance. The curve is the resonance shape resulting from the sum of a normal Breit-Wigner amplitude whose total width is $\Gamma = 26$ keV and a nonresonant amplitude corresponding to a background cross section of 0.32 mb.

photoneutron angular distribution will be isotropic; for $\frac{1}{2} \to \frac{3}{2} \to 0$, the ratio $R = d\sigma(90°)/d\sigma(135°)$ will be 1.43. Spins were assigned by observing the relative yields at 135° and 90° for each neutron group. The directional sensitivity of the experiment was calibrated by observing the yield for a resonance in ^{208}Pb(γ, n) at 255 keV, which is known to be isotropic. For narrow resonances, the yields could be estimated reliably by subtracting a background obtained by linear interpolation of the background in adjacent time-of-flight channels. The angular-distribution ratio obtained from these yields in every case corresponded to one of the two expected values within error. Where spin assignments could be made from other data (e.g., peak values of the total neutron cross section of ^{28}Si), they were consistent. However, some difficulty was encountered with the resonance at 761 keV. For this case, R was observed to be 1.20 ± 0.04—i.e., intermediate between the two expected values. We believe that this low value of R can be explained by the difficulty in estimating the appropriate instrumental background to be used to obtain the correct yield, particularly for the spectrum at 135°. Fortunately, the correct spin assignment $J^\pi = \frac{3}{2}^-$ is clearly indicated in the data of Schwartz, Schrack, and Heaton. The individual resonance yields were analyzed to determine the values of $g\Gamma_{\gamma_0}\Gamma_n/\Gamma$. From the total neutron cross-section data on ^{28}Si, it is clear that in each case $\Gamma_n/\Gamma \approx 1$, so that Γ_{γ_0} can be obtained from the yields and spin assignments.

The photoneutron data suggest that, as in the results for $n + {}^{28}$Si, the reaction strength is not uniformly distributed over the observed interval 6–1400 keV but rather is concentrated in the region above 500 keV. It is very improbable that the absence of photoneutron structure at lower energies could result from the influence of the neutron widths. Although photoneutron resonance yields are proportional to $\Gamma_{\gamma_0}\Gamma_n/\Gamma$, $\Gamma_n/\Gamma \approx 1$ for ^{29}Si even when the neutron decay is severely inhibited. Because $J^\pi = \frac{3}{2}^-$ for all the photoneutron resonances observed except those at 1093 and 552 keV, it is interesting to consider the possibility of an isolated doorway state consisting of a $2p_{3/2}$ neutron coupled to ^{28}Si near 750 keV ($E_{\rm exc} = 9.2$

MeV). The $2s_{1/2}$-$2p_{3/2}$ single-particle transition is predicted[8] to be concentrated near an excitation energy of 10 MeV for nuclei close to ^{32}S. In ^{29}Si the integrated radiative strength of $\frac{3}{2}^-$ resonances is 12 eV, i.e., roughly 10% of the value (~120 eV) expected for the $2s_{1/2}\to 2p_{3/2}$ transition by a valence neutron in ^{29}Si. Similarly the total neutron strength for these resonances is ~5% of the Wigner limit. Thus the data might be explained by the hypothesis of a $p_{3/2}$ doorway containing about 10% of the $2p_{3/2}$ neutron single-particle strength.

Lane[5] has shown that whenever the channel states of two reaction channels contain components of the same doorway states, the partial widths for the two reaction channels will be correlated. In the limit of a single common doorway, the correlation should be complete. The results of an analysis of the correlation between the ground-state radiation width Γ_{γ_0} observed for resonances in $^{29}\mathrm{Si}+n$ are shown in Fig. 2. The reduced widths were determined from observed values of Γ_n according to the relationship[9] $2P_1\gamma_n^2 = \Gamma_n$, where P_1 is the p-wave penetrability. A strong tendency of partial widths to correlate is evident in Fig. 2. This conclusion is confirmed by the value of the correlation coefficient

$$\rho = \frac{\sum(\Gamma_{\gamma_0}-\overline{\Gamma}_{\gamma_0})(\gamma_n^2-\overline{\gamma}_n^2)}{[\sum(\Gamma_{\gamma_0}-\overline{\Gamma}_{\gamma_0})^2\sum(\gamma_n^2-\overline{\gamma}_n^2)^2]^{1/2}} = 0.8$$

which is obtained for the eight $\frac{3}{2}^-$ resonances observed in the photon reaction. Also indicated in Fig. 2 are four weak p-wave resonances observed only in $^{28}\mathrm{Si}+n$. If these levels are included in the analysis, $\rho = 0.9$. These values suggest that the two groups of partial widths are almost completely correlated. However, since the large value of ρ results almost completely from the contribution of the 761-keV resonance, the existence of the correlation should be regarded as probable but not certain. The probability of obtaining the result $\rho > 0.8$ from eight paired observations is ≈ 0.05 when $\rho_{\mathrm{true}} = 0$.

Perhaps the most important feature of the photoneutron data is the strong interference effect observed for resonances at 530 and 761 keV. We limit the present discussion to the 761-keV level. Because the asymmetry in the shape of the 761-keV resonance is present at 90° and 135° with the same sign, interference with scattering amplitudes corresponding to $J^\pi = \frac{1}{2}^-$ and $\frac{1}{2}^+$ can be ruled out. The data indicate the presence of an interfering amplitude of spin and parity $\frac{3}{2}^-$. The magnitude of the latter amplitude was estimated by

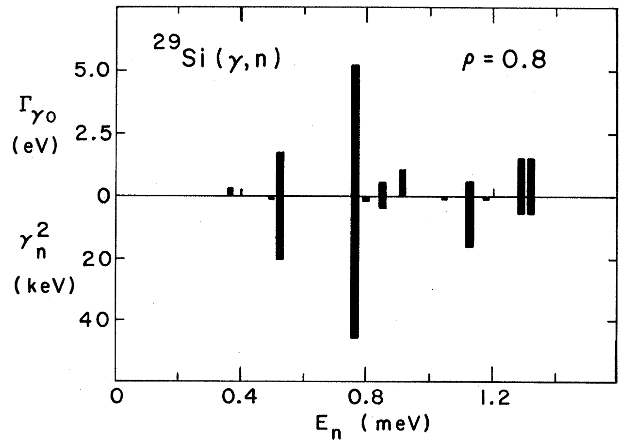

FIG. 2. Ground-state radiation widths Γ_{γ_0} and reduced neutron widths γ_n^2 for resonances in the ^{29}Si compound nucleus with $J^\pi = \frac{3}{2}^-$.

fitting the shape of the 761-keV resonance with a cross section resulting from the sum of a normal Breit-Wigner amplitude and a real nonresonant amplitude of opposite sign. The fit to the data shown in the inset of Fig. 1 was obtained in this way. The value of the total nonresonant cross section corresponding to this fit was $0.32^{+0.16}_{-0.12}$ mb, i.e., $d\sigma(90°)/d\Omega_{\mathrm{back}} = 0.034$ mb/sr. The error in this estimate results from the uncertainty in the shape and value of the background under the 761-keV level. Contributions from the tails of local resonances cannot account for the size of σ(back). Individually and cumulatively, the amplitudes calculated for the resonances in the region 0–14 MeV are at least a factor of 10 too small.

Lane has explored the relationship between correlations and background cross sections. He finds that a nonzero background cross section describing the contributions of the tails of distant resonances is implied by the observation of correlations. This σ(back) is proportional to the correlation coefficient according to the relationship

$$\sigma_{n\gamma_0}(\mathrm{back}) = \rho(\gamma_n^2, \Gamma_{\gamma_0})\sigma_n(\mathrm{abs})\frac{\Gamma_{\gamma_0}}{D}\left(\frac{\mathrm{Re}R_{n\gamma_0}}{\mathrm{Im}R_{n\gamma_0}}\right)^2,$$

where σ_n(abs) is the neutron absorption cross section,

$$\sigma_n(\mathrm{abs}) \equiv g(2\pi^2/K_n^2)\Gamma_n/D,$$

and $R_{n\gamma_0}$ is the appropriate element of the R matrix.[10] Using the value of $\overline{\Gamma}_n/D$ implied by the data of Schwartz, Schrack, and Heaton, the value of Γ_{γ_0}/D suggested by the photoneutron data, Lane's assumption that $\mathrm{Re}R/\mathrm{Im}R \approx 1$, and detailed balance, we find

$$\sigma_{\gamma_0 n}(\text{back}) \approx 0.1 \text{ mb}.$$

Because of the assumptions made, this result is a very approximate estimate of σ(back). However, the cross section actually measured is sufficiently close to this value to suggest that the data for ^{29}Si establish qualitatively the relationship between correlations and background cross sections developed by Lane.

In summary, the simultaneous observation in ^{29}Si of localized neutron and radiative strength, strong partial-width correlations, and a background cross section observable through its interference effects may be attributed to the presence of an isolated common doorway state consisting of a $2p_{3/2}$ neutron coupled to the ^{28}Si ground state. If this explanation is correct, it poses further questions. The observed $E1$ strength is distributed over an ~500-keV interval, a substantial fraction of a single particle width. Yet the observed photon and neutron strengths are only $\lesssim 10\%$ of the total expected for the $2s_{1/2} \rightarrow 2p_{3/2}$ transition. This suggests that the strength of this transition either is fractionated and spread over a large region of excitation or that the transition is inhibited for some reason. Further experimental study of $p_{3/2}$ strength in ^{29}Si would clarify this point.

The authors gratefully acknowledge the continuing technical support during these measurements of J. Specht, G. Mavrogenes, L. Rawson, and the linac operations group, and very useful comments from and discussion with J. P. Schiffer.

†Work performed under the auspices of the U. S. Atomic Energy Commission.

*Argonne Universities Association Pre-doctoral Fellow from the University of Cincinnati.

[1]H. Feshbach, A. K. Kerman, and R. H. Lemmer, Ann. Phys. (New York) 41, 230 (1967).

[2]J. A. Farrel, G. C. Kyker, Jr., E. G. Bilpuch, and H. W. Newson, Phys. Lett. 17, 286 (1965).

[3]R. J. Baglan, C. D. Bowman, and B. L. Berman, Phys. Rev. C 3, 2475 (1971).

[4]H. W. Newson, in *Statistical Properties in Nuclei*, edited by J. B. Garg (Plenum, New York, 1972), p. 309.

[5]A. M. Lane, Phys. Lett. 31B, 344 (1970), and Ann. Phys. (New York) 63, 171 (1971).

[6]H. E. Jackson and E. N. Strait, Phys. Rev. C 4, 1314 (1971).

[7]R. B. Schwartz, R. A. Schrack, and H. T. Heaton, Bull. Amer. Phys. Soc. 16, 495 (1971).

[8]S. A. Farris and J. M. Eisenberg, Nucl. Phys. 88, 241 (1966).

[9]J. E. Lynn, *The Theory of Neutron Resonance Reactions* (Clarendon Press, Oxford, England, 1968), p. 106.

[10]A. M. Lane and R. G. Thomas, Rev. Mod. Phys. 30, 257 (1958).

Condensed π^- Phase in Neutron-Star Matter*

R. F. Sawyer

Department of Physics, University of California, Santa Barbara, California 93106

(Received 29 March 1972)

It is argued that at some density, estimated at about 1 baryon/F^3, superdense nuclear matter will make a transition to a phase of approximately equal numbers of protons, neutrons, and π^- particles, the latter condensed in one or two plane-wave states of momentum ≈ 170 MeV/c. These conclusions are based on the conventional theory of the pion-nucleon interaction.

The properties of superdense matter in neutron-star interiors have been estimated by several authors, using various approaches.[1-5] However, these approaches have all begun from a simple basic picture for the matter, one in which the matter consists (for densities up to about 1 baryon/F^3) of a Fermi gas primarily composed of neutrons, with some protons and electrons, which interact with each other through the standard nucleon-nucleon potentials.

As densities grow larger than nuclear densities (0.15 baryons/F^3), the assumptions of these models become shakier. Such phenomena as large contributions from many-body forces, or an exotic ground state, or real mesons as constituents of the matter, all become more likely at higher densities.

As an example, let us consider the possibility of a condensed phase of π^- particles neutralized by an equal number of protons, the system also containing an equal number of neutrons. The interactions of a π^- of moderate momentum ($0.5m_\pi c$