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Doorway-State Effects in the $M1$ Radiative Excitation of p-Wave Resonances in ^{57}Fe†

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The reaction ^{57}Fe(γ,n) has been studied near threshold. Intermediate structure observed in a strong p-wave resonance structure excited by $M1$ transitions is interpreted in terms of a doorway state resulting from a particle-hole excitation of ^{57}Fe.

Special reaction mechanisms such as doorway states can produce strong local concentrations of strength in the radiative cross sections for highly excited nuclear states. The well-known doorway state discovered by Farrell *et al.*[1] in studies of the reaction ^{206}Pb(n, n') is an excellent example. Baglan, Bowman, and Berman[2] observed a corresponding concentration of strength in studies of the reaction ^{207}Pb(γ, n) near threshold. Both the envelope and the fine structure of the strength of $E1$ transitions in the region of photoneutron energies of 200–600 keV correlate with the neutron data of Farrell *et al.* This note presents evidence for very sharp concentrations of strength in the cross section for $M1$ radiative excitation of p-wave levels in ^{57}Fe. These concentrations might be associated with a doorway consisting of an $(f_{5/2})(f_{7/2})^{-1}$ particle-hole pair coupled to the ^{57}Fe ground state. The data, obtained from high-resolution studies of the photoneutron cross section near threshold for ^{57}Fe, constitute a large sampling of ground-state radiation widths for p-wave resonances which heretofore could be obtained from neutron-induced reactions only with the greatest difficulty.

The measurements were performed on the Argonne threshold photoneutron facility[3] at the high-current electron linac. A 40-g target of ^{57}Fe was irradiated by a pulsed bremsstrahlung beam with the end-point energy adjusted[4] so that the nuclear states excited by photon absorption can decay by neutron emission only via a transition to the ground state of ^{56}Fe. Neutron resonance groups corresponding to each of the states excited were observed by time-of-flight measurements, with the detector set to observe neutrons emitted at 90° and 135° relative to the photon beam. Data taken at 90° are shown in Fig. 1. Observations covering the low-energy region [Fig. 1(a)] were taken with a ^{6}Li-glass neutron detector, while those covering the higher-energy region [Fig. 1(b)] were made with a proton-recoil detector. From the extensive data available on s-wave resonances in the total cross section of ^{56}Fe,[5] a complete list of expected s-wave ($j=\frac{1}{2}^+$) levels can be obtained. Where the resonance structure was completely resolved, i.e., below 225 keV, a measurable yield in the (γ, n) spectrum was obtained for all but one of the known s-wave levels. However, the most prominent feature of the results for ^{57}Fe as well as for other nuclei studied in this region is the strength of resonances with $l > 0$. In Fig. 1(a) the integrated strength of the high-angular-momentum component is greater than that of the s-wave component.

To clarify this aspect of the data, the spins of strong neutron groups were determined by studying the angular distribution of the photoneutrons. Dipole absorption by the $\frac{1}{2}^-$ ground state of ^{57}Fe excites $\frac{1}{2}$ and $\frac{3}{2}$ states which then decay by neutron emission to the 0^+ ground state of ^{56}Fe. For the spin sequence $\frac{1}{2}\to\frac{1}{2}\to 0$, the photoneutron angular distribution will be isotropic; for $\frac{1}{2}\to\frac{3}{2}\to 0$, the ratio $d\sigma(90°)/d\sigma(135°)$ will be 1.43. Spin assignments were made by normalizing the data for 90° and 135° so that the relative yields gave isotropy for the strong s-wave level at 212 keV, and calculating the corresponding ratio for the other resonances. The intensity ratios observed were consistent with the assumption that only dipole photon absorption is important in the excitation process. The parities of resonances with $j=\frac{1}{2}$ were assigned by comparing the photoneutron results with the total neutron cross-section data on ^{56}Fe. The s-wave resonances ($j=\frac{1}{2}^+$) observed in this ^{56}Fe cross section were identified in the ^{57}Fe photoneutron spectra, and the remaining $j=\frac{1}{2}$ levels were assigned spin and parity $\frac{1}{2}^-$. Parity assignments for levels with $j=\frac{3}{2}$ could be complicated by the presence of d-wave photoneutrons.

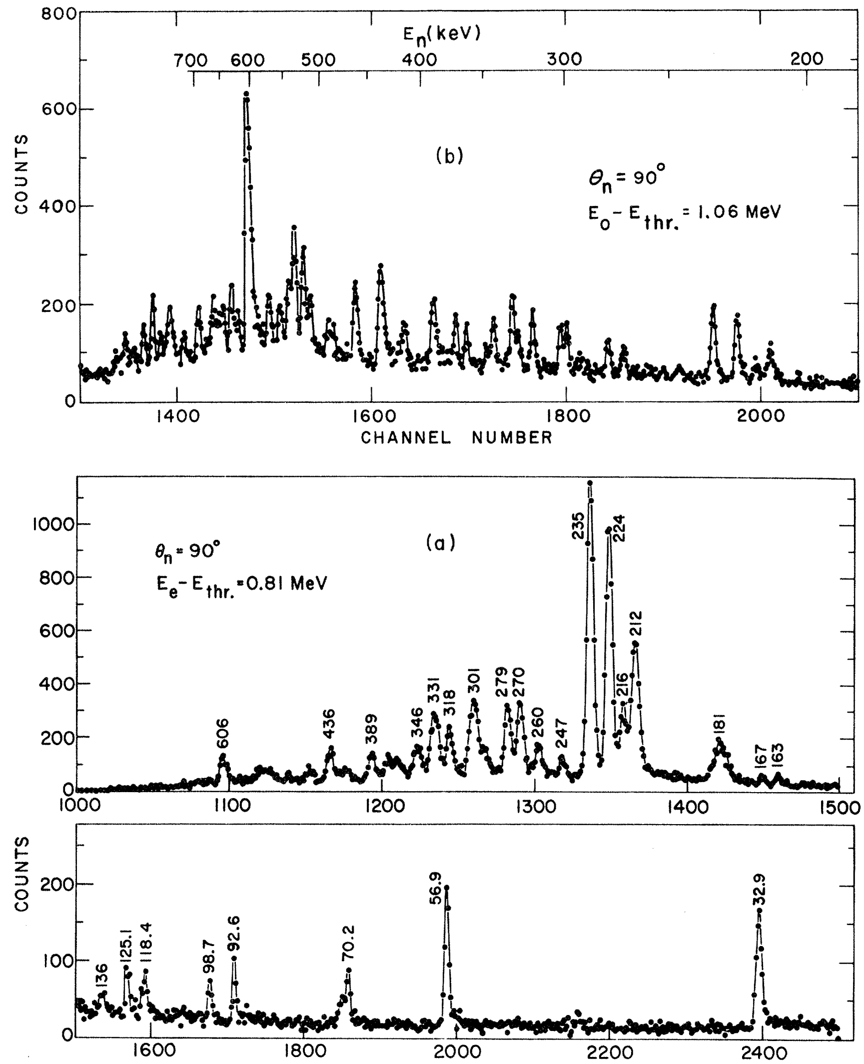

FIG. 1. Photoneutron time-of-flight spectra for $^{57}Fe(\gamma, n)$. (a) Portion observed with a ^{6}Li-glass detector; (b) the spectrum observed with a proton-recoil detector. The flight path was 9 m, the bremsstrahlung pulse width 6 nsec, the pulse repetition rate 800 pulses per second, and the average linac current ≈ 25 μA. The running time for each spectrum was approximately 24 h. The data shown have not been corrected for variations in detector efficiency or energy dependence of the incident photon flux. Resonance energies are in keV.

Our results for neighboring nuclei,[6] ^{53}Cr and ^{61}Ni, indicate that below 300 keV the d-wave neutron emission is not significant. Calculations of d-wave transmission coefficients from an optical-model potential support this conclusion. This suggests that the yield of d-wave resonances is inhibited by small values of Γ_n/Γ and that the probability of error is small in assigning all $j = \frac{3}{2}$ resonances a negative parity corresponding to p-wave emission. We have followed this convention for resonances below 300 keV and interpreted all of the resonance structure with $l > 0$ as a strong p-wave component excited by $M1$ transitions.

The feature of the data which we wish to emphasize here is that although the integrated $M1$ strength is consistent with prediction, it is anomalously concentrated in a few of the many resonances in the p-wave neutron channel. The individual resonance yields were analyzed to determine the values of $g\Gamma_{\gamma 0}\Gamma_n/\Gamma$. For all s-wave resonances and for p-wave levels above 100 keV, $\Gamma_n/\Gamma \approx 1$ so that $\Gamma_{\gamma 0}$ can be obtained from the yields and assignments. The s-wave and p-wave resonances give electric-dipole and magnetic-dipole partial radiation widths, respectively. The results are summarized graphically in Fig. 2 for all resonances whose spins could be assigned.

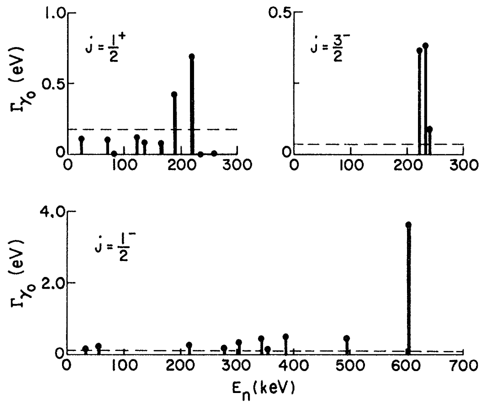

FIG. 2. Ground-state radiation widths $\Gamma_{\gamma 0}$ for resonances in the ^{57}Fe compound nucleus. Each resonance whose spin and parity is known is indicated at the resonance energy by a bar whose height is proportional to $\Gamma_{\gamma 0}$. Assignments for p-wave resonances with $j=\frac{3}{2}^-$ were limited to energies below 300 keV to avoid confusion with possible d-wave resonances. Because of the broad shape of s-wave levels at high neutron energies, assignments of s-wave structure were limited to the same range. For each of the three values of j^π for resonances, a dotted line indicates the average value $\bar{\Gamma}_{\gamma 0}$ inferred from the data below 300 keV.

No assignments were attempted for an unresolved structure of resonances between 515 and 556 keV because of uncertainty in the correct backgrounds. For both $E1$ and $M1$, the average radiative strength observed is consistent with the usual estimates. For $E1$ transitions, the reduced width $\bar{k}_{E1}\times 10^3 = 0.9^{+0.8}_{-0.3}$ is to be compared with the predicted value[7] 1.1; and for $M1$ transitions, $\bar{k}_{M1}\times 10^3 = 10^{+10}_{-3}$ is to be compared with the expected value[8] ~20. For p-wave resonances, however, the data of Fig. 2 contain two anomalous concentrations of strength. In the capture cross section of ^{56}Fe,[9] sixteen presumed p-wave levels were found below 130 keV, and results for s-wave levels would imply that about thirty resonances with $j^\pi=\frac{3}{2}^-$ should be found below 300 keV if the level density is proportional to $2j+1$. However, in the reaction ^{57}Fe(γ, n) below 300 keV we find only three resonances with $j^\pi=\frac{3}{2}^-$, including a very intense pair at 224 and 235 keV. Most of the $M1$ radiative strength for $\frac{3}{2}^-$ levels appears to be concentrated in this doublet, and such a concentration cannot be explained as a chance statistical fluctuation. We estimate less than 10^{-4} for the probability that the observed intense doublet might occur among thirty levels drawn from a Porter-Thomas distribution whose mean width is chosen to give the integrated strength observed for the $j=\frac{3}{2}^-$ levels plus all the unassigned p-wave levels.

At the same time, an extremely intense neutron group[10] with $j^\pi=\frac{1}{2}^-$ is observed at 606 keV. The spin and parity assignment of this level is based upon the isotropic angular distribution and the lack of correlation between the resonance energy and the s-wave resonances observed in the ^{56}Fe total neutron cross section. If the time-of-flight group is analyzed as a single resonance, the value $\Gamma_{\gamma 0}=3.6\pm 0.6$ eV is obtained. This value of $\Gamma_{\gamma 0}$ is over 40 times the average value of $\Gamma_{\gamma 0}$ observed for $j^\pi=\frac{1}{2}^-$ resonances below 300 keV (where the structure is resolved) and is more than twice the integrated strength expected for all $\frac{1}{2}^-$ levels in the 20–606-keV range. The probability is less than 10^{-3} of drawing such an intense width from a population of widths for levels with (1) the appropriate level spacing, (2) individual values of $\Gamma_{\gamma 0}$ which are uncorrelated and governed by a Porter-Thomas distribution, and (3) a $\bar{\Gamma}_{\gamma 0}$ which corresponds to an integrated radiative strength equal to twice the sum of the strengths observed in the 20–300-keV interval plus the strength in the 606-keV level. Even if the resonance were a doublet, the probability of generating the intense 606-keV neutron group is less than 10^{-2}.

Thus the photoneutron data provide strong evidence for intermediate structure in the cross section for radiative excitation of p-wave levels and therefore in the $M1$ radiative strength function. We suggest that this structure can be attributed to the presence of a strong two-quasiparticle doorway excitation[11] consisting of an $(f_{5/2})$-$(f_{7/2})^{-1}$ particle-hole pair coupled to the ^{57}Fe ground state. Calculations of energy eigenvalues above the Fermi energy in a Woods-Saxon potential[12] show that near $A=50$ the energy difference between the filled $1f_{7/2}$ level and the empty $1f_{5/2}$ orbital is about 8 MeV, quite close to the excitation energies studied in this experiment. A spin-flip transition in which an $f_{7/2}$ nucleon is transferred to the $f_{5/2}$ orbital would generate a doorway excitation of the appropriate spin, parity, and energy. The Weisskopf estimate[13] for such an $M1$ transition is ~11 eV, and polarization effects[14] can be expected to diminish this value. This is to be compared with the value $\Gamma_{\gamma 0}=3.6$ eV observed n the 606-keV resonance. Such a doorway would be expected to affect both the $j^\pi=\frac{1}{2}^-$ and $\frac{3}{2}^-$ channels since the particle-hole pair can couple to give either spin value. The resonance group near 220 keV would be the $\frac{3}{2}^-$ group. If this interpretation of the data is correct, it represents the limiting situation in which the damping widths[11] of the doorway states are so small that the strength of each doorway is spread over at most two or three resonances. In the case of the $\frac{1}{2}^-$ level at 606 keV, it appears to be concentrated in a single resonance.

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Possible Explanation for Gross-Structure Observations in the Direct Scattering of Helium Ions*

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A tentative explanation of the broad plateau observed in the spectra of directly scattered helium ions producing highly excited nuclear states is advanced. In the case of ^{4}He projectiles, we propose that, in addition to the suggested formation of short-lived ^{5}He (^{5}Li), the excitation of single-particle states in the continuum with and without subsequent nucleon emission can account for the data. Calculations are presented which corroborate this conjecture.

In a recent experimental investigation of the highly inelastic scattering of medium-energy (50–100 MeV) He ions by heavy nuclei,[1] a conspicuous plateau was observed (see Fig. 1) for incident ^{4}He at forward angles. This plateau could be ascribed to direct interactions; and it was suggested,[1] in the case of ^{4}He projectiles, that nucleon pickup and the formation of short-lived ^{5}He (^{5}Li) which subsequently break apart into a nucleon and α particle could account for at least a part of the higher-energy-loss portion of the plateaulike structure of the observed spectra. In this Letter we want to argue that *all* of the plateau can be accounted for by single-nucleon excitations to the continuum. Whereas, in the higher-energy-loss part of the plateau, it is necessary to consider the final-state interaction of the n-^{4}He (p-^{5}Li), we propose that it is the interactions of the neutron and ^{4}He with the target which dominate the reaction mechanism for the