EVIDENCE FOR THE EXCITATION OF TWO-PARTICLE, ONE-HOLE CONFIGURATIONS IN THE CAPTURE OF THERMAL NEUTRONS*

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In this note we shall be concerned with the strengths of primary electric dipole gamma-ray transitions to individual final states in the residual nucleus following capture of thermal neutrons. These (n,γ) strengths will be compared and contrasted with the reduced strengths, or spectroscopic factors, for $l=1$ (d,p) stripping on the same targets, leading to the same final states.

Earlier comparisons of (n,γ) and (d,p) strengths have been mostly confined to nuclei with $A \lesssim 40$.[1,2] The direct-capture[3] contribution to the (n,γ) cross section should, of course, be correlated with the (d,p) strength to the same final state. Bockelman[2] examined the available data in the light of the suggestion of Lane and Wilkinson[4] that the correlation might be somewhat more general. He found that in several cases there was indeed such a correlation; several other cases yielded ambiguous results or no correlation.

This note presents some results of a comparison of (n,γ) and (d,p) strengths[5] for nuclei with $40 \lesssim A \lesssim 65$. This region may be an especially good one for such a comparison, since neutron single-particle p states occur near the ground state for these nuclei, and the s-wave neutron strength function has a maximum in this region.[6] Data for $Fe^{56} \rightarrow Fe^{57}$ are collected in Fig. 1, and data for $Fe^{54} \rightarrow Fe^{55}$ in Fig. 2.

Similar comparisons may be made for several other nuclei in the $A \sim 60$ region; it is important, however, to have strengths, or meaningful upper limits, for most of the $\frac{1}{2}^-$ and $\frac{3}{2}^-$ levels over a reasonably large energy range, and for most cases the data are not as complete as for the residual nuclei Fe^{57} and Fe^{55}. The capture gam-

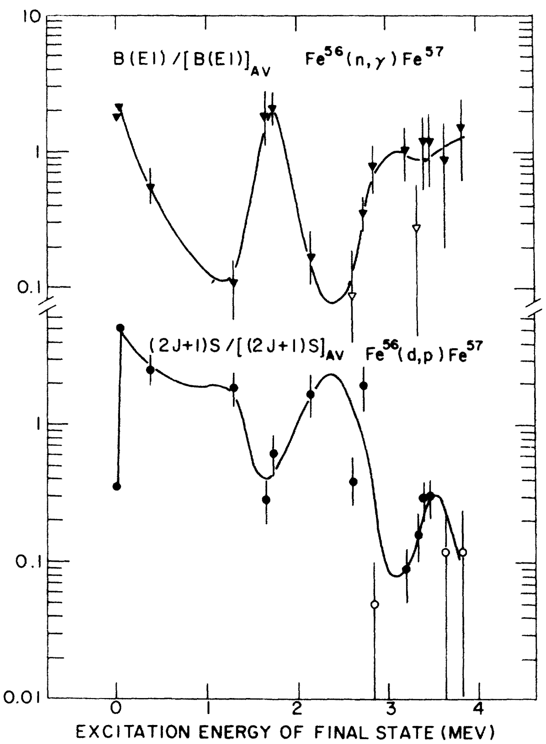

FIG. 1. Comparison of (n,γ) and (d,p) strengths for final states in Fe^{57}. The data are taken from references 8 and 10. The experimental data indicated by open circles and triangles are less definite than the others; the upper end of the uncertainty bar represents our estimate of the upper limit for that strength.

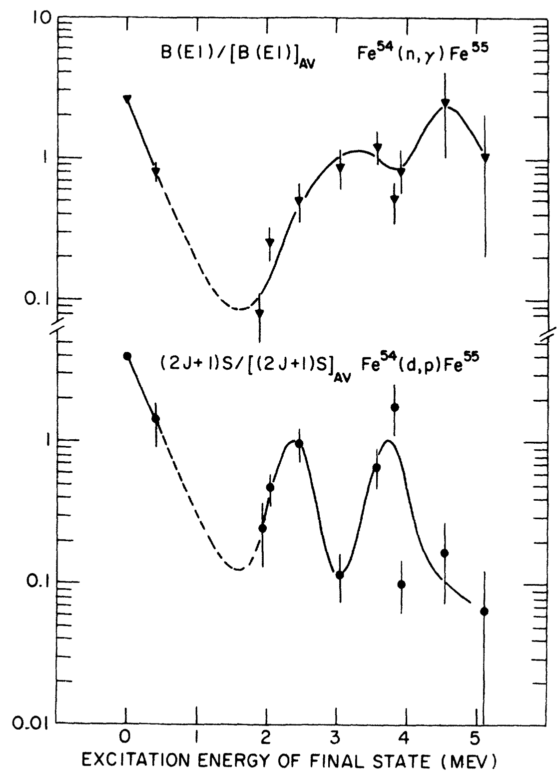

FIG. 2. Comparison of (n,γ) and (d,p) strengths for final states in Fe^{55}. The data are taken from references 7 and 9.

ma rays in Fe^{55} have recently been measured,[7] and there are two independent measurements of the capture gamma rays[8] in Fe^{57} and of the stripping strengths to final states in Fe^{55} [9] and Fe^{57}.[10] In all major respects these independent measurements are mutually consistent. We have limited consideration to states below about half the neutron separation energy; with this limitation as well as, in most cases, some knowledge of the gamma rays in coincidence with the transition considered, and/or agreement with a (d,p) energy, the number of gamma rays included which are not primary may be expected to be small.

The striking features evident in Figs. 1 and 2 are the following:

(i) There are regions of excitation where $B(E1)$ is large, but which cannot be associated with single-particle p states observed in stripping.

(ii) There is, in fact, an anticorrelation between the values of $B(E1)$ and the stripping spectroscopic factor, except in the region of the $p_{3/2}$ single-neutron state.

(iii) In some cases (e.g., Fe^{57} 1.7-MeV region), the non-p-state regions where $B(E1)$ is large have a rather narrow energy spread, of the order of a few hundred keV.

The same features are also seen in plots like Figs. 1 and 2 for other nuclei in this region (e.g., Cr^{53}, Ni^{61}, etc.).

In elucidating the nature of these capture gamma-ray transitions, it may be pertinent to consider the following information:

(a) The energy of the lowest "anomalous region of strong $B(E1)$" is about twice the energy of the first 2^+ state in neighboring even-even nuclei; this energy is also approximately equal to the "energy gap," the energy at which, in the even-even nuclei, the lowest seniority-two configurations (except for the first 2^+ state) are found.

(b) Many of the states which are excited with large $E1$ strength in neutron capture, but low stripping strength in the (d,p) reaction, decay by gamma-ray emission mostly to the ground state (or, in Fe^{57}, to the ground-state doublet).[11] For example, the decay of the 3.04-MeV state in Fe^{55} is about 60% to the ground $(p_{3/2})$ state.[7]

(c) In the case of the 2.32-MeV level in Cr^{53}, which is much more strongly excited in the (n,γ) reaction than in the (d,p) reaction, the multipolarity of the transition to the ground $(p_{3/2})$ state is 99% $M1$ and ~1% $E2$.[12] The gamma-ray width of this level has been measured by resonant scattering, and the mean life deduced is $(4\pm2)\times10^{-15}$ sec.[13] This corresponds to $M1$ and $E2$ transitions of about single-proton speed.

(d) While the application of statistical analysis to such small samples of data is of somewhat questionable reliability, it seems that while the distribution of $l=1$ stripping strengths in these nuclei are approximately described by a Porter-Thomas distribution,[14] the distributions of $B(E1)$ values are not; the value of ν, the "number of degrees of freedom," derived from fitting a χ^2 distribution to the $B(E1)$ data is about three.

The anticorrelation of the $B(E1)$ values with the stripping strengths (except near the ground state) shows that many of the important capture gamma-ray transitions are not due to direct capture. On the other hand, the existence of peaks and valleys in plots like Figs. 1 and 2 leads to the conclusion that a substantial part of the (n,γ) reaction is not proceeding through fully developed compound states. The statistical analysis, though it cannot be relied upon heavily, supports this conclusion.

A natural framework for discussion of these regions of anomalous $E1$ strength is found, however, in the concept of the "doorway state."[15] It is suggested that the states (other than single-neutron p states) strongly excited in neutron capture are states of seniority three (or, equivalently, two-particle, one-hole states), and that the gamma-ray decay to these states occurs from two-particle, one-hole components in the wave function of the capturing state. The number of two-particle, one-hole states near the neutron binding energy has been estimated for various cases by Shakin[16] and by Lande and Block.[17] For nuclei in this region also, one can estimate that there are about three two-particle, one-hole states per MeV near the neutron binding energy. For Fe^{55}, for example, the two-proton, one-neutron state $[(f_{7/2})_p^{-1}(f_{5/2})_p(d_{5/2})_n]_{1/2^+}$ is expected near the neutron binding energy; this state has allowed $E1$ transitions to the states

$$[(f_{7/2})_p^{-1}(f_{5/2})_p(p_{3/2})_n]_{1/2^-,3/2^-},$$

which are expected at about 4 MeV. The latter, in turn, have allowed $M1$ and $E2$ transitions to the $p_{3/2}$ ground state. Similar configurations involving two neutrons and a neutron hole are available. For $N=31$ nuclei (e.g., Fe^{57}) there are also configurations involving recoupling of the last three neutrons. All these seniority-three configurations are, of course, not excited in the direct-reaction (d,p) process.

It should be noted that some of the seniority-three excitations near the neutron binding energy have allowed $E1$ transitions to seniority-one (single-neutron) configurations. For example, the three-neutron configurations

$$[(f_{7/2})^{-1}(g_{9/2})(p_{3/2 \text{ or } 1/2})]_{1/2^+}$$

have allowed $E1$ transitions to the single-neutron $p_{3/2}$ and $p_{1/2}$ configurations, respectively. Transitions of this type may be expected to contribute strongly to the direct population in the (n,γ) reaction of the states populated strongly in stripping.[18]

It is, of course, not excluded by the evidence summarized above that some of the $E1$ strength to the lower-lying seniority-three excitations is due to seniority-five components in the capturing state; the number of appropriate seniority-five configurations near that energy is so small, however, that this contribution to the $E1$ transition probability can be expected to be small.

It will probably not be possible to make definite assignments of the available configurations either to the seniority-three components of the capturing states or to the regions where $B(E1)$, but not the stripping strength, is large, until more information is available on the energies of the proton-hole states, and on the lifetimes and multipole mixtures of the gamma-ray transitions de-exciting the strongly fed levels.

It is interesting to examine other reactions which lead to the same set of final states as the (n,γ) and (d,p) reactions. There may be regions of incident energy where such a reaction proceeds mainly through "doorway state" configurations; if such is the case one would see the seniority-three (and seniority-one) configurations populated strongly, just as appears to be the case in the (n,γ) reaction. The only available data known to us which are detailed enough for such a comparison are recently published data on the $Fe^{57}(p,p')$ reaction at 7 MeV incident energy.[19] The (p,p') intensities are compared with the (n,γ) strengths in Fig. 3, and can be seen to be not inconsistent with the hypothesis that the two reactions proceed by a similar mechanism.[20]

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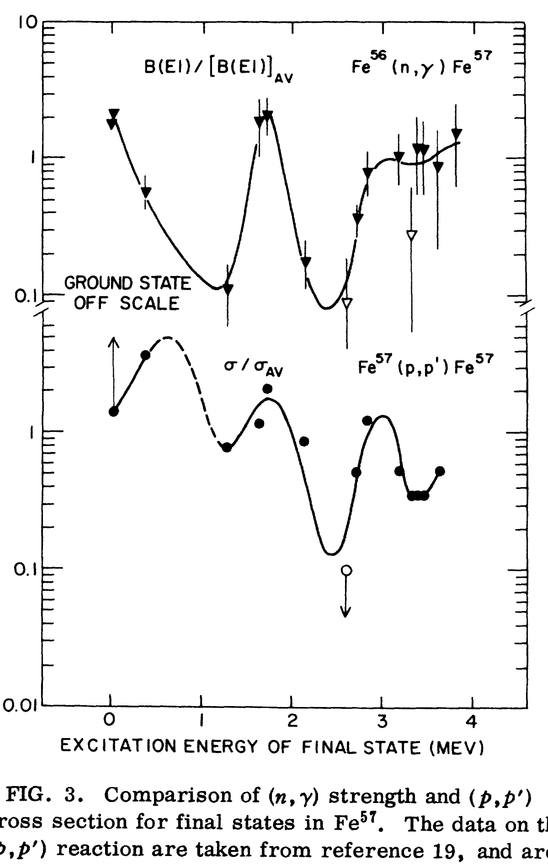

FIG. 3. Comparison of (n,γ) strength and (p,p') cross section for final states in Fe^{57}. The data on the (p,p') reaction are taken from reference 19, and are for 7-MeV incident energy and laboratory scattering angle of 130°. The point for the 14-keV state is only an estimate.

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[5]We shall use $I(\gamma_i)/E^3(\gamma_i) \equiv B_i(E1)$ as a measure of the $E1$ strength between the capturing state and the individual final states of a particular residual nucleus; the conclusions are not sensitive to the assumed energy dependence. We shall use the spectroscopic factor multiplied by the statistical factor, $(2J+1)S$, as a measure of the $l=1$ (d,p) stripping strength.

[6]Nuclei with $A \sim 190$ are also of interest because they also meet these criteria.

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[11]The ground state of Fe^{57} is known to be predominantly of seniority three. See, for example, B. J. Raz, B. Zeidman, and J. L. Yntema, Phys. Rev. 120, 1730 (1960); I. Hamamoto and A. Arima, Nucl. Phys. 37, 457 (1962).

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[16]C. Shakin, reference 15.

[17]A. Lande and B. Block, Phys. Rev. Letters 12, 334 (1964).

[18]Estimates of the "single-particle transition probability" for capture gamma-ray transitions to single-particle states usually involve a ratio D/D_0, where D is the compound-nucleus level spacing and D_0 is a single-particle level spacing. [See J. M. Blatt and V. F. Weisskopf, Theoretical Nuclear Physics (John Wiley & Sons, New York, 1952), p. 644, and G. A. Bartholomew, reference 1, p. 273.] In those cases where important contributions can be made by seniority-three to seniority-one transitions, D_0 should perhaps be taken as the average spacing for all levels which have allowed single-particle matrix elements to the seniority-one final state. This may increase the estimated single-particle transition probability.

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[20]The large (p,p') intensity to the 0.37-MeV state is perhaps connected with the strong excitation of collective levels usually found in inelastic scattering.

OFF-SHELL CORRECTION IN PION PHOTOPRODUCTION

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In this note we present some preliminary results of analyzing pion photoproduction data[1,2] by taking into account the virtuality of the exchanged pion in the Drell model.[3,4]

Ferrari and Selleri[5] derived an approximate expression for the off-shell pion-nucleon 3,3 scattering amplitude containing an unknown pionic form factor $K(\Delta^2)$ depending only on Δ^2, the square of the four-momentum of the virtual pion. They applied their result to an analysis,[6] on the basis of the one-pion exchange (OPE) mechanism, of single-pion production data from nucleon-nucleon collisions. It is shown that in the calculation of the amplitude for this process there occurs the function

$$\Phi(\Delta^2)=K^2(\Delta^2)K'(\Delta^2)\psi(\Delta^2) \qquad (1)$$

where $K(\Delta^2)$ appears twice since it is associated with each pion-nucleon vertex, $K'(\Delta^2)$ contains all the higher order corrections to the pion propagator, and $\psi(\Delta^2)$ is a known function depending on the parameters of the 3, 3 resonance. The moderate success they met in substantiating the OPE by fitting this data with an empirical function $\Phi(\Delta^2)$ suggests the importance of a similar calculation in the case of photoproduction.

Drell's expression[3] for photoproduction of negative pions from a heavy target nucleus A is

$$\frac{d^2\sigma}{dp\,d\Omega}=\frac{\alpha}{8\pi^2}\left(\frac{\sin\theta}{1-\beta\cos\theta}\right)^2\frac{p(k-\omega)}{k^3}\sigma_A(T) \qquad (2)$$

where the photon has energy k, the pion of mass μ is observed in solid angle $d\Omega$ about θ and in momentum interval dp about p. The corresponding energy is ω, the velocity is β, and total π^+-A cross section at kinetic energy $T=k-\omega-\mu$ is $\sigma_A(T)$. In Drell's terminology, the photon pro-