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Evidence for Nonstatistical Effects in the Reaction $Dy^{163}(n,\gamma)Dy^{164}$†

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γ-ray intensities from 17 resonances with $J=3$ to 22 final states in Dy^{164} reveal that there are significant correlations between partial radiative widths and reduced neutron widths. The two-particle, one-hole doorway-state concept and channel-capture mechanisms may be invoked to explain these correlations.

Experimental data which have accumulated in the past two years indicate that there are significant departures from the extreme statistical model of nuclear reactions in the neutron-capture process. A positive correlation between reduced neutron widths and partial radiative widths has been established[1] for the target nucleus Tm^{169}, and enhanced transitions to positive-parity states at low excitation energies in Nb^{94} have been observed.[2] The channel-capture process of Lane and Lynn[3] has been invoked in order to explain the Tm^{169} results[4] while the concept of the two-particle, one-hole (2p-1h) doorway states has been advanced in order to understand the Nb results. In addition, enhanced γ radiation at $E_\gamma \approx 5$ MeV was observed[5] in the $(d,p\gamma)$ and the (n,γ) reactions in elements near the closed neutron shells 82 and 126. An interpretation in terms of the doorway state was first proposed by Bartholomew et al., whereby an incoming neutron interacts with a target nucleus to form a 2p-1h state, and subsequently a particle and a hole combine to yield the resulting enhanced γ radiation.

Recently Lane[6] attempted to explain on theoretical grounds the reported value of the correlation for Tm^{169} in terms of the concept of the doorway state. A parallel development in terms of the same concept is advanced by Beer.[7] Lane showed that under special simplifying conditions the correlation coefficient ρ' between amplitudes of reduced neutron widths and partial radiative width is related to the number of contributing doorway states n, i.e., $\rho' \approx n^{-1/2}$. Thus a correlation coefficient between partial radiation widths and reduced neutron widths of $\rho = 0.27$ for Tm^{169} implies the presence of about four doorway states.

In this Letter we would like to report evidence for nonstatistical effects in Dy^{163}. The present investigation was highly motivated by certain remarkable results[8] of the total neutron cross-section work for elements in the rare-earth region. A high degree of positive correlation between total radiative widths and the s-wave neutron strength functions was observed for the dysprosium isotopes. One way of interpreting[8] this is that, for the same isotope, a correlation between partial radiative widths and reduced neutron widths may exist for quite a few final states. If this supposition is proved true, it would imply that nonstatistical effects, such as channel capture or 2p-1h effects, play an important role in the radiative process. The fact that the 4s single-particle states are located at about the neutron separation energy in this mass region suggests that single-particle effects may contribute to the radiative process. The crucial requirement is the establishment of a positive correlation between the (n,γ) and (d,p) intensities to the same set of final states on one hand and partial radiative widths and reduced neutron widths on the other hand. On the other hand, the variation[8] of the s-wave neutron strength function S^0 with mass number for the Dy isotopes suggests that the 2p-1h doorway states have an influence on S^0, as was demonstrated by Shakin[9] for the tin isotopes.

In order to gain more insight into this problem, we investigated the γ-ray spectra resulting from neutron capture in individual resonances of Dy^{163}. The spins of resonances have been determined[10] by the methods of examining the primary and secondary γ rays. A list of γ-ray energies and intensities will be published shortly.

The reduced intensities of observed γ rays averaged over 17 resonances are illustrated in Fig. 1. Several interesting features manifest

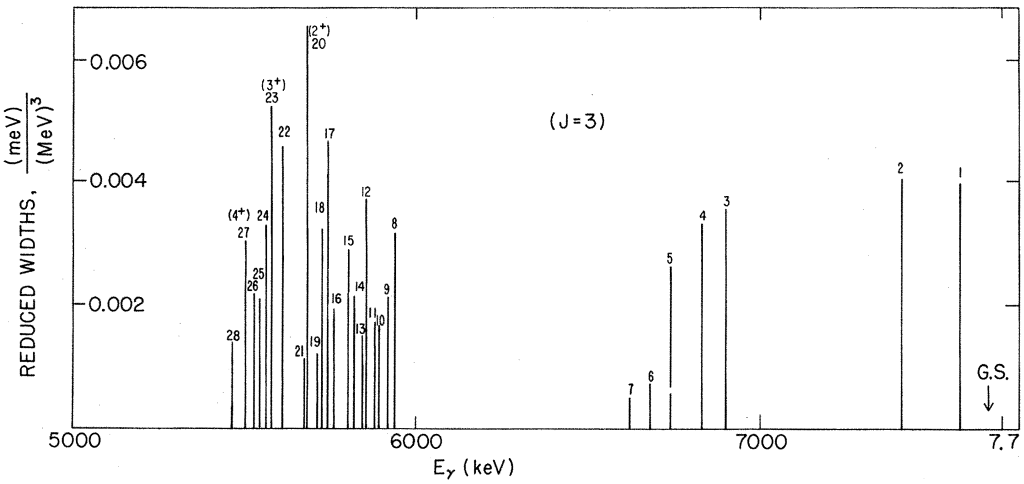

FIG. 1. A plot of the reduced intensities averaged over 17 resonances of Dy^{163} versus the γ-ray energy. The arrow indicates the position of the ground-state transition.

themselves here.

(1) No γ rays are observed between lines 7 and 8. The energy difference between these two lines is about equal to the energy gap in even-even deformed nuclei, i.e., it is equal to the energy required to break a neutron pair.

(2) The low-lying states corresponding to lines 1 to 5 are strongly populated in the (n,γ) reaction and in the (d,d') reaction but not in the (d,p) data of Shelton and Sheline.[11] This feature of the data is not in accord with the channel-capture process proposed by Lane and Lynn.[3]

(3) The intensity ratio of lines 20, 22, and 27 is about the same as in the (d,p) data. (Compare Fig. 1 here with Fig. 1 of Ref. 11.) Since these states are strongly excited in the (d,p) reaction, Shelton and Sheline suggested that the nature of these states is much different from that of the rotational and vibrational states at low energy. Accordingly these states are interpreted[11] in terms of a superposition of two quasiparticle neutron states of Nilsson orbitals $\frac{5}{2}^-[523]$ and $\frac{1}{2}^-[521]$. The wave functions of these states resemble more closely that of the target nucleus plus a neutron than they do the low-lying rotational states. Unfortunately, since neither spectroscopic factors nor cross-section values are reported[11] and only a limited number of transitions to final states of known spin is available, no quantitative measure of the correlation coefficient between the (n,γ) and the (d,p) results can be given.

A strong evidence for the nonstatistical aspects of the (n,γ) reaction in Dy^{163} comes from a study of the correlation coefficient ρ between partial radiation widths and reduced neutron widths for the low-lying states (lines 1 to 5) and the states at excitation energy of 1978 (line 20), 2051 (line 22), and 2153 keV (line 27). A correlation analysis of these five γ rays (lines 1 to 5) from 17 resonances with $J=3$ shows that there is a positive and substantial correlation between partial radiation widths and reduced neutron widths. An average value

$$\langle\rho\rangle=\frac{1}{5}\sum_{j=1}^{5}\rho_j=0.353$$

is found. A statistical analysis in terms of a Monte Carlo calculation with the aid of code CORNROW[12] establishes that such a value is very significant as described in Fig. 2(a). It is noteworthy that the ρ_j's for each of the individual four γ rays (excluding peak 5) have confidence factors larger than 90%. In addition, it is interesting to point out that eight $J=2$ resonances do not exhibit any significant correlation. A similar type of analysis for γ rays 20, 22, and 27 reveals that the correlation coefficient for them is 0.357. As shown in Fig. 2(b), this value is again significant. To consider the matter further, we carried out a correlation analysis for 22 γ rays from 17 resonances excluding only 5 $M1$ transitions. Again, as illustrated in Fig. 2(c), a value of $\langle\rho\rangle=0.223$ is very significant. This analysis establishes that nonstatistical effects play an important and significant role in the radiative process in Dy^{163}. In accordance with Lane's[6] picture, we suggest that there are a few isolated common doorway states which are producing these significant positive correlations. It is of particular interest to find out whether these doorway states have any effect on the s-wave neutron strength

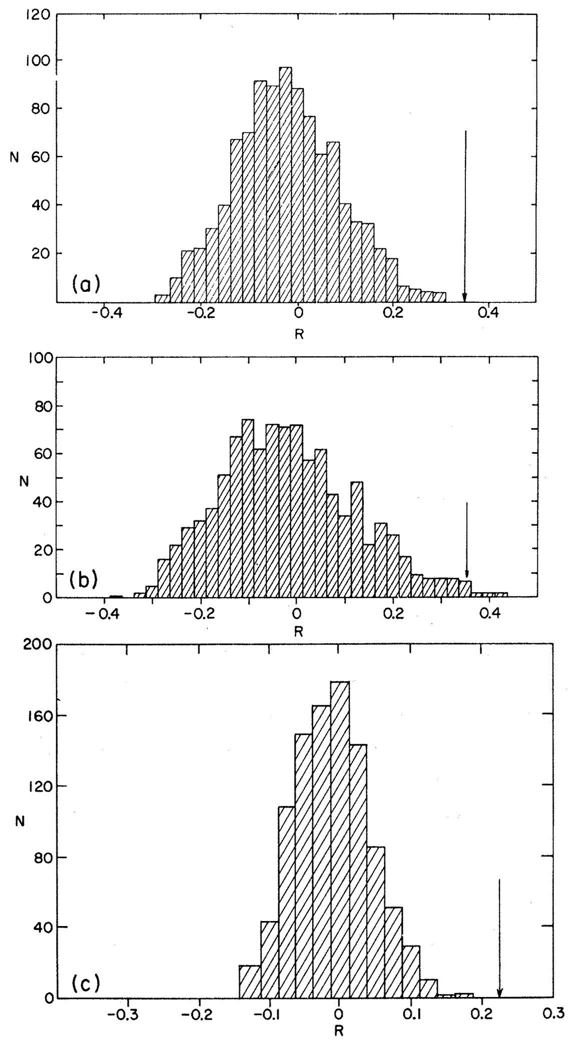

FIG. 2. The distribution of the correlation coefficient of partial radiation width $\Gamma_{\gamma ij}$, and reduced neutron width Γ_{ni}^0, in $Dy^{163}(n,\gamma)Dy^{164}$ for (a) 5 final states below the energy gap, (b) the two-quasiparticle neutron states, and (c) 22 final states. The experimentally determined average correlation R_E in each case is also shown by the arrows.

function of the two spin states $J=2$ and $J=3$. Calculating this quantity in the energy region up to 323 eV, one gets the following results: $S^0(J=2) = 0.54 \pm 0.26$, $S^0(J=3) = 1.24 \pm 0.40$. Although the values just overlap within their statistical errors, they are suggestive of spin dependence of the neutron strength function which in turn suggests intermediate structure. What can be said about the higher energy states, particularly those corresponding to lines 20, 22, and 27? According to the (d,p) data, these states have more single-particle character in them than do the low-lying rotational states. The facts (1) that these states are strongly excited in the (n,γ) reaction, (2) that their intensity ratio is qualitatively the same in the (n,γ) as in the (d,p) data, and finally (3) that they manifest strong correlations between $\Gamma_{\gamma ij}$ and Γ_{ni}^0 indicates that valency nucleon effects or channel capture are contributing to the radiative process. According to Lynn,[13] the important neutron transitions around this mass region are $4s_{1/2} \to 3p_{3/2}$, $4s_{1/2} \to 3p_{1/2}$, $3d_{5/2} \to 3p_{3/2}$, $3d_{5/2} \to 2f_{5/2}$, and $1j_{15/2} \to 1i_{13/2}$. The mean energy of these is about 5.5 MeV. Note that lines 20, 22, and 27 have energies of 5.680, 5.607, and 5.505 MeV. In addition the wave function of these states has a component of the $p_{3/2}$ Nilsson orbital. These considerations lead us to adopt the following model for Dy^{163}. This nucleus can be pcitured as a core of Dy^{162} and a single particle in an $f_{5/2}$ orbital. An incoming $s_{1/2}$ neutron may interact with the core exciting another neutron into an unfilled orbital thus creating a hole. This configuration would correspond to the 2p-1h doorway state. The particle and the hole would subsequently combine emitting a γ ray. This process would account for the correlations observed for the low-lying states. On the other hand, the incoming $s_{1/2}$ neutron may be captured "directly" into a $p_{3/2}$ orbital emitting a γ ray during the process. The configuration of these two quasiparticles would correspond to the excited states corresponding to lines 20, 22, and 27. This model seems to be consistent with observations.

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Absolute Tensor-Polarization Calibration of a Polarized Deuteron Beam*

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The tensor analyzing power A_{yy} of ^{4}He$(d, d)^4$He has been calibrated absolutely at $\theta_{\text{lab}} = 55°$, $E = 7.07$ MeV using the reaction ^{16}O$(d, \alpha_1)^{14}$N*(2.31). A value of $A_{yy} = -1.066 \pm 0.034$ was obtained.

Much of the relatively precise deuteron polarization data which have been published in recent years have been limited in accuracy by uncertainty (≈10%) in the calibration of the tensor polarization of the deuteron beams from polarized-ion sources. It has been pointed out by Jacobsohn and Ryndin[1] that nuclear reactions for which the target and both outgoing particles have zero spin can be used to calibrate absolutely the tensor polarization of incident spin-1 particles. For such reactions the vector analyzing power vanishes and the tensor analyzing power is determined solely by conservation laws and is independent of energy, angle, and reaction mechanism. It is the purpose of this note to report the use of this technique in the calibration of ^{4}He$(d, d)^4$He scattering as a secondary standard. As a calibration reaction ^{16}O$(d, \alpha_1)^{14}$N*(2.31) was chosen, since cross-section measurements[2] for this isospin-forbidden reaction indicate reasonably large (≈0.7 mb/sr) values for the cross section at certain energies and angles, and the α_1 group can be separated relatively easily from the other particle groups. For routine beam-calibration measurements a far more practical process than the reaction ^{16}O(d, α_1) is ^{4}He$(d, d)^4$He scattering, because of its much larger cross section and because it has an appreciable analyzing power which varies smoothly with energy.

For these measurements, the spin-symmetry axis of the tensor-polarized deuteron beam from the Notre Dame Lamb-shift source[3] was vertical, and the beam was accelerated to an energy of 7.42 MeV. A 1.25-cm-diam gas target filled with a mixture (2:1 by pressure) of ^{4}He and O_2 at a pressure of 3 atm absolute was used. Energy loss in the steel foil (4 μm) and the gas reduced the deuteron energy at the center of the target to 7.07 ± 0.02 MeV. α particles emitted at ±35° were detected by a pair of 50-μm surface-barrier detectors. It was necessary to subtract a small background from under the α_1 peak in the α-particle spectrum. This background, which appeared to arise from straggling and slit scattering, amounted to about 6% of the counts under the peak for spectra taken with the polarized beam, and about 11% for spectra taken with the unpolarized beam. Deuterons elastically scattered from ^{4}He at $\theta_{\text{lab}} = \pm 55°$ were detected in surface-barrier detectors. Depletion thicknesses of both the alpha and deuteron detectors were adjusted with detector bias so as to stop mainly the particles of interest and remove the less densely ionizing particles to a lower region of the pulse-height spectrum. Aluminum foils were placed in front of the 55° detectors to stop the α particles. By simultaneously detecting α particles from ^{16}O$(d, \alpha_1)^{14}$N* and deuterons elastically scattered from ^{4}He, it was possible to eliminate the effects of variation in beam polarization on the calibration of ^{4}He$(d, d)^4$He.

The quantity measured was

$$Q = \frac{\sigma_p}{\sigma_u}\bigg|_L + \frac{\sigma_p}{\sigma_u}\bigg|_R - 2 = P_{zz} A_{yy}, \tag{1}$$

where subscripts p, u, L, and R denote polarized, unpolarized, left, and right, respectively. The incident beam polarization referred to its spin-symmetry axis is given by P_{zz}, and A_{yy} denotes the analyzing power for the reaction in question,[4] and is defined in accordance with the Madison convention.[5] For the reaction ^{16}O$(d, \alpha_1)^{14}$N*,[1] $A_{yy} = -2$, so that $Q_{d,\alpha_1} = -2P_{zz}$. Using this result and Eq. (1), one obtains from the mea-