PHYSICAL REVIEW C VOLUME 8, NUMBER 4 OCTOBER 1973

Neutron Polarization in Isospin-Forbidden (p, n) Reactions*

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(Received 17 May 1973)

It is shown that the angular distributions of the yield and of the polarization of neutrons in isospin-forbidden (p,n) reactions can provide a test of the statistical assumptions that are usually made in the analysis of isobaric-analog-resonance reactions. Also, under certain specified conditions, such measurements can detect any significant neutron width acquired by the analog state via Coulomb mixing with the $T_<$ background states. Recent measurements of the yield and polarization for the $^{51}V(p,n)^{51}Cr$ reaction in the neighborhood of the analog resonance observed at a proton energy of ~2.335 MeV are discussed in terms of the present results. However, this particular example provides no unambiguous information about the mechanism that causes a breakdown of the statistical model or about a possible enhancement of the neutron width in the vicinity of the analog.

I. INTRODUCTION

Most of the spectroscopic information that has been derived from isobaric-analog-resonance reactions has been based on the assumption that their fine structure (consisting of states with isospin $T_<$ that is one unit less than the isospin $T_>$ of the analog) could be treated statistically.[1] Recently,[2] the validity of this assumption has been questioned. The purpose of this paper is to show that measurements of the angular distribution of the neutron yield and polarization in isospin-forbidden (p, n) reactions can provide a test of this assumption.

The present paper is structured as follows. In Sec. II an R-matrix description of isobaric-analog-resonance reactions is specialized to the case of isospin-forbidden (p, n) reactions. The general expression for the energy-averaged (p, n) collision-matrix elements is discussed in terms of the statistical approximation and in terms of special states that can induce correlations that invalidate this approximation. In Sec. III, it is shown that information about the nature of any correlations among the background (fine-structure) states can be obtained from measurements of the neutron differential cross section and polarization. Also discussed are the conditions necessary that such measurements be sensitive to any nonzero neutron width acquired by the analog via Coulomb mixing with distant $T_<$ states. The question whether an analog state acquires a significant neutron width via Coulomb mixing with $T_<$ states is one of the major unsolved problems in analog-state studies and (p, n) polarization measurements may complement other investigations[3] of this question. In Sec. IV, recent $^{51}V(p, n)^{51}Cr$ data are discussed in terms of the distribution of $T_<$ states in ^{52}Cr in the neighborhood of the analog of the 1.559-MeV level in ^{52}V. Finally, Sec. V contains a few brief comments on the present results and on possible future measurements of this type.

II. COLLISION-MATRIX ELEMENTS FOR THE ISOSPIN-FORBIDDEN (p,n) REACTION

Consider the (p, n) reaction over an energy interval such that the compound system contains a single analog state superposed on a background of $T_<$ states. The collision-matrix elements that describe this process will be discussed in terms of the R-matrix formalism proposed by Bloch[4] and developed further by Robson and Lane.[5] In addition to the physical Hamiltonian H and the outgoing-wave boundary condition operator L that define a complete set of states of the compound system, these latter authors introduce an "ideal" Hamiltonian H^0 and a (real) boundary-condition operator L^0 such that the eigenstates of $H^0 + L^0$ are the analog state $|\lambda\rangle$ and the $T_<$ states $|\mu\rangle$.

In terms of these states the (n, p) element of the collision matrix $U^{J\pi}$ is

$$U_{np} = 2i \exp[i(\omega_p - \phi_p - \phi_n)] P_n{}^{1/2} P_p{}^{1/2} G_{np}, \qquad (2.1)$$

where ϕ_c and ω_c are the usual hard-sphere and Coulomb phase shifts, P_c is the penetrability,

$$G_{np} = \sum_\nu (E_\nu - E)^{-1} \gamma_{\nu n} (\gamma_{\nu p} - \langle\lambda|h|\nu\rangle \alpha_{\lambda p}/\epsilon_\lambda), \qquad (2.2)$$

$$h = (H - H^0) + (L - L^0) \equiv \Delta H + \Delta L, \qquad (2.3)$$

$$\alpha_{\lambda p} = \gamma_{\lambda p} - \sum_\nu (E_\nu - E)^{-1} \langle\lambda|h|\nu\rangle \gamma_{\nu p}, \qquad (2.4)$$

$$\epsilon_\lambda = E_\lambda - E + \langle\lambda|h|\lambda\rangle - \sum_\nu (E_\nu - E)^{-1} \langle\lambda|h|\nu\rangle^2 . \qquad (2.5)$$

Here $\gamma_{\nu c}$ is the reduced-width amplitude in channel c for states $|\nu\rangle$ that diagonalize the Hamiltonian

H in the space of the $T_<$ states, i.e.,

$$Q_\mu(H+L-E_\nu)Q_\mu\,|\,\nu\rangle=0\ , \tag{2.6}$$

where

$$Q_\mu=\sum_\mu|\,\mu\rangle\langle\mu\,|\ . \tag{2.7}$$

Equation (2.2) shows that the contribution from the analog state $|\lambda\rangle$ to the (p, n) reaction is determined by the matrix elements $\langle\lambda\,|h|\,\nu\rangle=\langle\lambda\,|\Delta H|\,\nu\rangle+\langle\lambda\,|\Delta L|\,\nu\rangle$, where

$$\langle\lambda\,|\,\Delta L\,|\,\nu\rangle=-\sum_c(S_c+iP_c-b_c)\gamma_{\lambda c}\gamma_{\nu c}\ . \tag{2.8}$$

Here S_c is the shift function and b_c is the boundary condition imposed on the states $|\lambda\rangle$ and $|\mu\rangle$ at the surface $r_c=a_c$ in channel c. Since these states have good isospin, channels in which the fragments are members of the same isospin multiplet must have identical boundary conditions. In particular, for the proton channel p_c with target nucleus in state $|C\rangle$ and the corresponding neutron channel n_c with residual nucleus in the isobaric analog of state $|C\rangle$, it is necessary that $b_{p_c}=b_{n_c}$ and $a_{p_c}=a_{n_c}$. If the b_{n_c} are chosen equal to S_{n_c}, these conditions can be used to eliminate the (closed) n_c channels from the sum in Eq. (2.8) so that

$$\langle\lambda\,|\,\Delta L\,|\,\nu\rangle\equiv\sum_c\Delta L_c\gamma_{\nu c}\gamma_{\lambda c}\ , \tag{2.9}$$

where

$$\Delta L_c\equiv L_{n_c}-L_{p_c}=S_{n_c}-(S_{p_c}+iP_{p_c})\ . \tag{2.10}$$

The matrix element (2.8) is usually referred to as external mixing, while $\langle\lambda\,|\Delta H|\,\nu\rangle$ is the contribution due to internal mixing.

Since our primary purpose is the analysis of neutron polarization and angular distributions that presently can be measured in isospin-forbidden (p, n) reactions, it is realistic to confine our attention to the gross-structure features of such processes. Thus we consider the collision matrix elements U_{np} averaged over the fine-structure fluctuations associated with the ν states. For an averaging interval δ that is larger than the mean spacing of the ν levels but is smaller than the energy range over which the analog structure is pronounced, the averaged collision matrix elements are defined in terms of a Lorentzian weighting function so that

$$\langle U_{np}(E)\rangle_{\rm av}=U_{np}(E+i\delta)\ . \tag{2.11}$$

The channel quantities ϕ_c, ω_c, and P_c in Eq. (2.1) usually can be considered to be constant within δ so that $\langle U_{np}\rangle_{\rm av}$ is proportional to $\langle G_{np}\rangle_{\rm av}$, where

$$\langle G_{np}\rangle_{\rm av}=R^b_{np}-M_{\lambda n}(\gamma_{\lambda p}-M_{\lambda p})/(E_\lambda-E+\Phi_\lambda)\ , \tag{2.12}$$

$$R^b_{cc'}\equiv\langle\sum_\nu(E_\nu-E)^{-1}\gamma_{\nu c}\gamma_{\nu c'}\rangle_{\rm av}\ , \tag{2.13}$$

$$M_{\lambda c}\equiv\langle\sum_\nu(E_\nu-E)^{-1}\langle\lambda\,|h|\,\nu\rangle\gamma_{\nu c}\rangle_{\rm av}\ , \tag{2.14}$$

$$\Phi_\lambda\equiv\langle\lambda|h|\lambda\rangle-\langle\sum_\nu(E_\nu-E)^{-1}\langle\lambda|h|\,\nu\rangle^2\rangle_{\rm av}\ . \tag{2.15}$$

In order to reduce Eq. (2.12) to a tractable form, it is necessary to introduce approximations for the energy-averaged quantities $M_{\lambda c}$ and Φ_λ. The assumption usually made[6] in a consideration of analog-resonance reactions is that for all channels c

$$[\gamma_{\nu c}\gamma_{\nu c'}]=[\gamma_{\nu c}{}^2]\delta_{cc'}\ , \tag{2.16}$$

$$[\gamma_{\nu c}\langle\lambda|\,\Delta H\,|\,\nu\rangle]=0\ , \tag{2.17}$$

where $[\cdots]$ denotes an average over those states $|\,\nu\rangle$ for which E_ν is within δ of E. Equation (2.16) is the usual assumption underlying the Hauser-Feshbach[7] theory and Eq. (2.17) is the natural extension of this assumption to the analog state. With these assumptions, Eq. (2.14) with $c=n$ implies

$$M_{\lambda n}=0\ , \tag{2.18}$$

and Eq. (2.15) becomes

$$\Phi_\lambda=\sum_c\Delta L_c\gamma_{\lambda c}{}^2(1-\Delta L_c\,R^b_{cc})+\Phi^I_\lambda\ . \tag{2.19}$$

Here Φ^I_λ is defined by replacing h with ΔH in Eq. (2.15). Note that $\langle G_{np}\rangle_{\rm av}$ will contain a contribution from the analog state $|\lambda\rangle$ only if $M_{\lambda n}\neq0$, i.e., only if the statistical assumptions (2.16) and/or (2.17) are violated.

Lane[2] has pointed out that values of the width $\mathrm{Im}\Phi_\lambda$ predicted by Eq. (2.19) are in serious disagreement with existing data. Since observed elastic-channel reduced widths $\gamma_{\lambda p}{}^2$ do not exhaust the Teichmann-Wigner[8] sum rule, inelastic channels that are coupled to the analog state $|\lambda\rangle$ cannot be ignored in Eq. (2.19). In particular, Eq. (2.19) contains a contribution to $\mathrm{Im}\Phi_\lambda$ of the form

$$\sum_{c-}(\Delta L_{c-})^2\gamma_{\lambda c-}{}^2\,\mathrm{Im}R^b_{c-c-}\ , \tag{2.20}$$

where the sum is over the closed channels c^- that are coupled to the state $|\lambda\rangle$. In Ref. 2 this contribution is estimated to be several times the value of the widths usually observed in analog-resonance reactions. This implies that the statistical assumptions (2.16) and (2.17) are not valid and that important phase-correlation effects have been neglected in the derivation of Eqs. (2.18) and (2.19).

It is suggested by Lane[2] that the only systematic source of such correlations is the admixture in the background states $|\nu\rangle$ of isobaric-analog-configuration states. These are shell-model states that have the same configurations as, but with isospin one unit less than, that of the analog state. If the reduced-width amplitudes $\gamma_{\nu c}$ of the fine-structure states are determined primarily by admixtures from the configuration states $|\alpha\rangle$, i.e., if

$$\gamma_{\nu c} = \sum_{\alpha} \gamma_{\alpha c} \langle \alpha | \nu \rangle , \tag{2.21}$$

then Eqs. (2.13)–(2.15) become

$$R^{b}_{cc'} = \sum_{\alpha\alpha'} s_{\alpha\alpha'} \gamma_{\alpha c} \gamma_{\alpha' c'} \tag{2.22}$$

$$M_{\lambda c} = \sum_{\alpha\alpha'} s_{\alpha\alpha'} \gamma_{\alpha c} F_{\lambda\alpha'} , \tag{2.23}$$

$$\bar{\Phi}_{\lambda} = \sum_{c} \Delta L_c \gamma_{\lambda c}{}^2 + \langle \lambda | \Delta H | \lambda \rangle - \sum_{\alpha\alpha'} s_{\alpha\alpha'} F_{\lambda\alpha} F_{\lambda\alpha'} , \tag{2.24}$$

where

$$s_{\alpha\alpha'} \equiv \Big\langle \sum_{\nu} (E_\nu - E)^{-1} \langle \alpha | \nu \rangle \langle \alpha' | \nu \rangle \Big\rangle_{\text{av}} , \tag{2.25}$$

$$F_{\lambda\alpha} \equiv \sum_{c} \Delta L_c \gamma_{\lambda c} \gamma_{\alpha c} + \langle \alpha | \Delta H | \lambda \rangle . \tag{2.26}$$

That the correlations induced by the configuration states can give results in agreement with observed values of $\text{Im}\Phi_\lambda$ has been demonstrated in Ref. 2. The essential point is that if the states $|\lambda\rangle$ and $|\alpha\rangle$ are orthogonal, i.e., if

$$\sum_{c} \gamma_{\lambda c} \gamma_{\alpha c} = 0 , \tag{2.27}$$

and if ΔL_c were independent of c, then the first term in Eq. (2.26) would vanish. For the negative-energy proton channels c^-, the quantity ΔL_{c^-} is a slowly varying function of c so that these correlations drastically reduce the contribution of the negative-energy channels to the width $\text{Im}\Phi_\lambda$.

From a comparison of R-matrix and shell-model prescriptions for the evaluation of $\text{Im}\Phi_\lambda$, Mahaux and Weidenmüller[6] conclude: (1) that $(\Delta L_{c^-})^2$ decreases (approximately exponentially) with increasing separation between the threshold energy for the c^- channel and the energy E_λ of the analog state, (2) that Lane neglected this energy dependence and consequently overestimated the contribution from Eq. (2.20) to the width $\text{Im}\Phi_\lambda$, and therefore (3) that the statistical assumptions used to obtain Eqs. (2.18)–(2.19) are not necessarily in conflict with available data.

It is not our purpose to discuss here the relative merits of the arguments presented in Refs. 2 and 6. The statistical approximation is an essential part of the theory that is presently used to abstract nuclear-structure information from data on isobaric-analog-resonance reactions. It is, therefore, of interest to investigate any experiments that could provide a direct test of the validity of this approximation.

Equations (2.22)–(2.24) are based on the assumption (i) that the only source of correlation between the background states ν is that due to their configuration-state[9] components. The characteristics of the angular distribution of neutrons emitted in the (p, n) reaction will give some indication of the validity of this assumption. Further, let us make the assumption (ii) that not all configuration states have zero width for decay into the observed neutron channel (or channels). In the context of (i), assumption (ii) is necessary in order to obtain nonzero values for the energy-averaged quantities R^{b}_{pn}, $M_{\lambda n}$, and $\langle U_{np}\rangle_{\text{av}}$. The possibility that any resonant contribution to the neutron polarization in isospin-forbidden (p, n) reactions depends on such correlations suggests that a study of this quantity could provide information about the configuration states and their role in analog-resonance reactions. Some qualitative details of such a study are outlined in Sec. III.

III. NEUTRON ANGULAR DISTRIBUTIONS AND POLARIZATION

Some information about the distribution of the fine-structure states and about the nature of any correlations between them can be obtained from general features of the neutron polarization and angular distributions. This follows from the following well-known[10] properties of these distributions. (a) The neutron angular distribution is asymmetric about $\theta_{\text{c.m.}} = 90°$ only if energy-averaged collision-matrix elements for states of opposite parity contribute to the reaction. (b) The neutron polarization (for unpolarized protons incident on unpolarized targets) vanishes unless there is interference between two or more exit (neutron) channels.

In applying these properties to the isospin-forbidden (p, n) reaction, it is convenient to specify the collision-matrix elements more precisely. Let $U^{J\pi}_{cc'}$ denote the collision-matrix elements for the transition from channel c' to c where $J\pi$ is the spin and parity of the total system. The symbol c contains all of the quantum numbers necessary to identify a given channel uniquely. For the (p, n) reaction, the elements of interest are $U^{J\pi}_{n_i p_j}$, where (for example) n_i represents the set of quantum numbers $\{EljI\}_i$ that uniquely specify a particular neutron channel. Here E_i and I_i are, respectively, the internal energy and spin of the final state of the residual nucleus, l_i is the orbital angular momentum of the relative motion of the neutron and the residual nucleus, $j_i = l_i \pm \frac{1}{2}$, and $|j_i - I_i| \leq J \leq j_i + I_i$.

Let the spin and parity of the analog state be J_λ and π_λ so that the collision-matrix elements considered in Sec. II are now written as $U_{n_i p_j}^{J_\lambda \pi_\lambda}$. Usually there are other matrix elements $U_{n_i p_j}^{J\pi}$ that contribute to the observed (p, n) reaction. We make the reasonable assumption that all elements of $U^{J\pi}$ are uncorrelated with all elements of $U^{J'\pi'}$ for $J'\pi' \neq J\pi$ so that for all such matrix elements

$$\langle U^{J\pi} U^{J'\pi'}\rangle_{\text{av}} = \langle U^{J\pi}\rangle_{\text{av}} \langle U^{J'\pi'}\rangle_{\text{av}} . \tag{3.1}$$

The general expression for the differential cross section in a (p, n) reaction will involve sums of products of collision matrix elements that have the form $\text{Re}[(U_{np}^{J_\lambda \pi_\lambda})^* U_{np}^{J\pi}]$. The measured energy-averaged differential cross section can be written as the sum of a direct-reaction cross section, which is obtained by substituting $\langle U\rangle_{\text{av}}$ for U in the expression for the cross section, and an energy-averaged fluctuation cross section which is proportional to $\langle (U_{np}^{J_\lambda \pi_\lambda} - \langle U_{np}^{J_\lambda \pi_\lambda}\rangle_{\text{av}})^* (U_{np}^{J\pi} - \langle U_{np}^{J\pi}\rangle_{\text{av}})\rangle_{\text{av}}$. If the deviations of U_{np} from its energy-averaged value are considered to be random, the fluctuation cross section can be estimated in a fashion similar to the Hauser-Feshbach result except that the transmission coefficients[11] are redefined to be $T_c = 1 - \sum_{c'} |\langle U_{cc'}\rangle_{\text{av}}|^2$. Since the coefficient T_p is resonant in the neighborhood of E_λ, it follows that the observation of a resonance in $\sigma_{pn}(\theta)$ is *not*, of itself, evidence for a nonzero value of $M_{\lambda n}$.

Consider first a neutron angular distribution that is observed to be asymmetric about $\theta_{\text{c.m.}} = 90°$ for proton energies in the neighborhood of an analog resonance. Suppose further that the neutron yield exhibits a resonance-like shape as a function of proton energy in this neighborhood. Property (a) then implies nonzero values for the energy-averaged matrix elements $\langle U_{np}^{J_\lambda \pi_\lambda}\rangle_{\text{av}}$ and $\langle U_{np}^{J\pi}\rangle_{\text{av}}$, where $\pi = -\pi_\lambda$. This, in turn, leads to the conclusion that either (i) the statistical approximation is invalid not only for $T_<$ states of spin and parity J_λ and π_λ but also for $T_<$ states of parity $-\pi_\lambda$ or (ii) there are two analog states of opposite parity in the energy region of interest. These alternatives lead to qualitatively different predictions of the way in which the asymmetry of the angular distribution will change as the proton energy is varied over the energy interval containing the analog state (or states). Thus, at least in principle, the measured neutron angular distribution could distinguish between these possibilities.

If the neutron angular distributions are observed to be asymmetric about $\theta_{\text{c.m.}} = 90°$, a measurement of the neutron polarization serves as a useful complement to the angular distribution since the above alternatives (i) and (ii) lead to qualitatively different energy dependences of this quantity also. This is discussed more fully in Sec. IV. However, a measurement of the neutron polarization is potentially more interesting for those reactions in which the angular distribution is symmetric and in which neutron decay of the analog is possible in two channels n_1 and n_2. The symmetry of the angular distribution implies that $\langle U_{np}^{J\pi}\rangle_{\text{av}} = 0$ for at least one value of the parity π, and it seems reasonable to assume that $\langle U_{np}^{J\pi}\rangle_{\text{av}}$ can be set equal to zero for all nonanalog values of $J\pi$. In this situation a nonzero result for the neutron polarization would imply some special correlations among the $T_<$ states of the same $J_\lambda \pi_\lambda$ as the analog. Specifically, in terms of the configuration-state hypothesis, such a result would imply that configuration states, which mix with the background states $|\nu\rangle$, have nonzero width for decay into neutron channels n_1 and n_2. Further, if the polarization shows the resonance at E_λ, then the "neutron width of the analog" $M_{\lambda n}$ does not vanish.

IV. DATA ANALYSIS: ^{51}V$(p,n)^{51}$Cr REACTION

As an example of the procedure outlined in Secs. II and III, an analysis of the ^{51}V$(p, n)^{51}$Cr reaction in the vicinity of an analog resonance will now be described. In a study of the ^{51}V$(p, \gamma)^{52}$Cr reaction, Teranishi and Furubayashi[12] identified a number of ^{52}Cr resonances as isobaric analogs of low-lying states in ^{52}V. The most prominent resonance in this work is one observed at a proton energy of ~2.335 MeV, whose parent (the 1.559-MeV level in ^{52}V) is believed[13] to have spin and parity 4+. Teranishi and Furubayashi[12] also measured relative cross sections for the ^{51}V$(p, n)^{51}$Cr reaction in the neighborhood of this resonance and found that the neutron angular distribution was symmetric (about the 90° c.m. angle) at an energy corresponding to the peak of the resonance, and that the asymmetry in the plot of neutron yield as a function of proton energy was different from that usually associated with isobaric analog resonances (i.e., the interference minimum was observed to be lower in energy than the maximum). For an isolated analog state formed through a single proton channel, the asymmetry in the neutron yield will depend on the parameters that define that particular channel. In the case of the ^{51}V$(p, n)^{51}$Cr reaction through a 4+ analog resonance, both $p_{1/2}$ and $p_{3/2}$ proton channels may be strongly coupled to the analog. Under these conditions the asymmetry in the yield will depend on the parameters associated with both proton channels. Thus, the asymmetry in the yield may be different from that normally expected.

Because of this, and in the light of the discussion in Secs. II and III, there seemed to be particular interest in remeasuring the neutron yield and angular distribution and measuring the neutron polarization near this resonance.

These measurements have been carried out at the Argonne Dynamitron accelerator. The experimental arrangement, method, and results are described elsewhere,[14] as are any conclusions relating to the spin, parity, and other properties of the resonances of interest. Two results are of primary concern for the purposes of the present study. The first is that when the measured differential cross sections were expanded into a series of Legendre polynomials with coefficients B_L, the values of B_1 in the neighborhood of the analog resonance at ~2.335 MeV are nonzero (though small) and exhibit a resonance-like energy dependence characterized by a peak near 2.335 MeV. The second result involves the measured polarization and is illustrated in Fig. 1. The values of the polarization are observed to be nonzero near 2.335 MeV and to show an energy dependence which closely resembles that of the measured yield.

The observation of nonzero resonant values of odd-order Legendre polynomial coefficients, although in disagreement with the earlier work of Teranishi and Furubayashi,[12] is consistent with a recent report by Egan *et al.*,[13] in which a single angular distribution measured at the peak of the resonance was found to be asymmetric about $\theta_{c.m.} = 90°$. As discussed in Sec. III, this asymmetry implies that compound-nucleus states with parity opposite to that of the analog resonance participate in the reaction, so that an interpretation of the results requires nonvanishing matrix elements $\langle U_{n_t p_j}^{J\pi}\rangle_{av}$ with $\pi = -\pi_\lambda$ as well as nonzero matrix elements $\langle U_{n_t p_j}^{J_\lambda \pi_\lambda}\rangle$ associated with the analog state of interest. Consequently the direct-reaction contributions to the differential cross section could not be neglected in this case. Although this result leads to a situation that is uninteresting from the point of view of determining unambiguously any information about the value of the parameter $M_{\lambda n}$, it is nonetheless of importance in the interpretation of the reaction mechanism.

As seen in Fig. 1, a small second "bump" is observed at an energy near 2.35 MeV. We performed a number of calculations of the neutron yield for the case of a single analog state coupled to two incident and two exit channels but could not reproduce these observations. However, both the polarization and the cross section were then computed on the assumption that the second peak corresponds in another analog state in ^{52}Cr (whose parent might be the level in ^{52}V at 1.577 MeV excitation[15]), and the results are shown in Fig. 2. It is assumed in these calculations that the energy dependence of the fluctuation cross section is the same as that

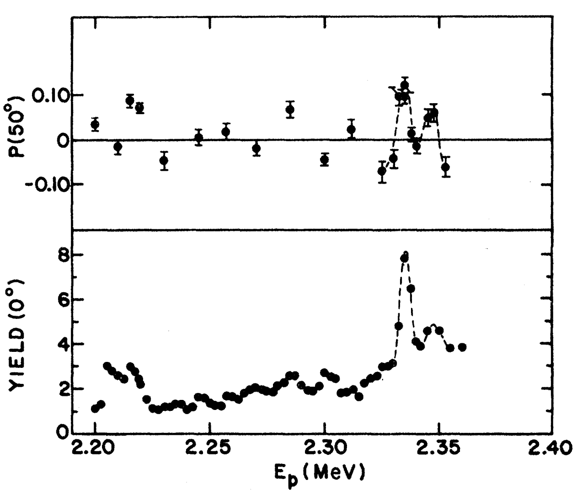

FIG. 1. The energy dependence of the neutron polarization measured at 50°, and the neutron yield (arbitrary units) measured at 0°, in the $^{51}V(p, n)^{51}Cr$ reaction. The experimental procedure is described in Ref. 14. The energy region of interest for the discussion of the present paper is the neighborhood of the analog resonances near 2.335 MeV. The dashed curves are drawn to guide the eye.

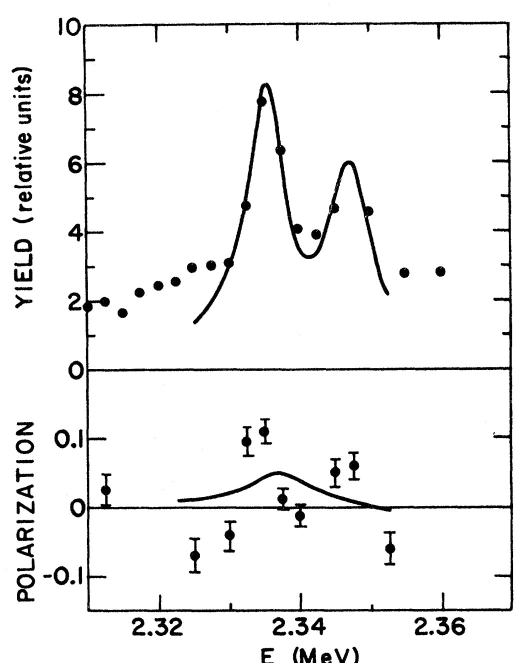

FIG. 2. The energy dependence of the neutron yield and polarization in the neighborhood of the analog resonances near 2.335 MeV. The solid curves are calculations based on the assumption of two analog resonances (at 2.335 and 2.348 MeV) only, each treated in the single-proton-channel approximation.

of the direct-interaction cross section, and the various coefficients are combined into a minimal set of "energy-independent" parameters that are determined by means of a least-squares adjustment to the data. This considerably simplified the calculations and, since we were interested only in the energy dependence of the various measured quantities, such a procedure seemed sufficient. The smooth curve represents the calculation in which the two analogs at 2.335 and 2.348 MeV are treated in the single-channel approximation.[16] The parameters associated with the 2.335-MeV state were set equal to the values given by Sekharen and Mehta[17] in a recent publication, in which these authors further suggest that the addition of a state near a proton energy of 2.35 MeV can successfully account for the previously observed "anomalous" asymmetry in the neutron yield as a function of proton energy in the neighborhood of the 2.335-MeV analog state.

As seen in Fig. 2, the calculated cross section

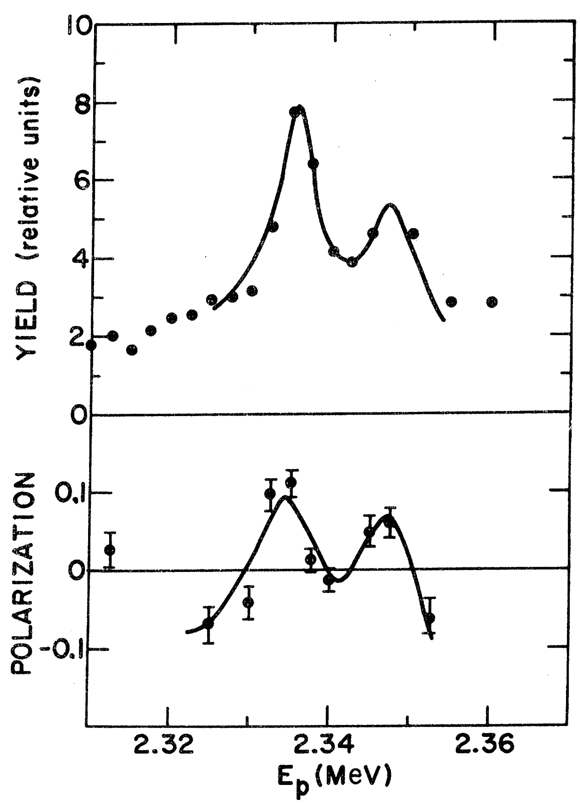

FIG. 3. The energy dependence of the neutron yield and polarization in the neighborhood of the analog resonances near 2.335 MeV. The solid curves are calculations based on the assumption of two analog resonances (at 2.335 and 2.348 MeV) plus a contribution from the inclusion of a nonresonant background in the vicinity of the resonance structure. Each analog state is treated in the single-proton-channel approximation.

accounts fairly successfully for the energy dependence of the measured yield. The measured polarization, however, is not adequately represented. It appears, therefore, that the existence of two interfering analog resonances does not in itself provide an adequate explanation of the experimental results.

A more nearly complete description of the data can be obtained by including a nonresonant background in the vicinity of the resonant structure. Figure 3 represents such a calculation, which includes the contributions that arise from interference between each resonance and the background amplitudes, as well as the interference between the two analog resonances themselves. As shown, the agreement between the calculations and the measurements is good.

Unfortunately, an accurate two-channel representation of each analog resonance was not possible.[16] However, for at least one set of parameters, the observed polarization in the neighborhood of the 2.335-MeV resonance could be approximately fitted on the basis of interference in the two exit channels of this state alone. For this situation, though, the values of the proton parameters were clearly unphysical.

It appears therefore that the calculations shown in Fig. 3 represent the simplest interpretation consistent with the observations. The need for the inclusion of background-resonance interference terms suggests that the statistical approximation is invalid not only for $T_<(J_\lambda \pi_\lambda)$ states but also for other background states of different $J\pi$. This conclusion is consistent with the conjecture that correlation mixing exists for the $T_<(J_\lambda \pi_\lambda)$ states and for the other background states as well. More probably, however, these results imply that the background states are not sufficiently dense to permit a statistical description of the ^{51}V$(p, n)^{51}$Cr reaction at the energies involved in the present work.

It should be mentioned that the polarization calculations are based on the assumption that the polarization of neutrons arising from the compound-nucleus (fluctuation) part of the yield is zero. With this assumption the present results require that $M_{\lambda n}$ be nonzero for at least one neutron channel n. However, the interpretation of the formal separation of the (p, n) cross section into a direct and a compound-nucleus part is complicated by the apparent low density of $T_<$ states in the region of the analog and, in this example, a nonzero $M_{\lambda n}$ is no longer a necessary consequence of the resonance-like behavior observed in the polarization data.

Finally, on the basis of results[15] from the ^{51}V $(d, p)^{52}$V reaction in which the parent levels are populated, both the analog state at 2.335 MeV and the proposed state at 2.348 MeV are expected to have positive parity. Thus, the observed nonzero resonant values of the B_1 coefficients are expected to arise through interference with negative-parity background states formed largely at these energies through s-wave interactions. This conclusion is supported by the fact that the experimental values[14] of B_1 (and the polarization as well) at energies outside of the resonance regions are consistent with zero. Apparently the neighborhood of the p-wave analog resonances is the only region in which the p-wave transmission coefficients are large enough to interfere significantly with the underlying s-wave background states and thereby to produce the nonzero B_1 coefficients and contribute to the observed nonzero polarization.

V. CONCLUSION

Unfortunately, the present analysis of the $^{51}V(p, n)^{51}Cr$ reaction is complicated by the existence of two closely-spaced analog states within the energy interval of interest and by the apparent low density of $T_<$ states in the region of the analogs. Consequently, this analysis does not give unambiguous information about the conjectured[2] existence of correlations among fine-structure states of the same symmetry as the analog nor does it answer satisfactorily the question about the existence of nonzero neutron widths of the analog. However, these results do indicate the complementary nature of differential-cross-section and polarization measurements in the investigation of the distributions of $T_<$ fine-structure states.

One of the principal results of this paper may be the specification of experimental conditions sufficient for the investigation of possible enhancement of neutron widths by the analog state. More nearly direct measurements[3] of such an enhancement include (p, n) yields in which the individual fine-structure states are resolved and $\gamma_{\nu n}{}^2$ is evaluated for energies E_ν in the neighborhood of the analog, (α, n) yields which imply that $M_{\lambda\alpha}$ and/or $M_{\lambda n}$ are nonzero, and (n, n) yields which depend on $M_{\lambda n}$. To date none of these measurements have answered unambiguously the question whether or not the analog acquires a significant neutron width via Coulomb mixing with $T_<$ states. In order to obtain an unambiguous answer to this question from (p, n) polarization measurements, it is important, certainly, to select nuclei of high enough mass numbers and with well-separated analog levels at high enough excitation energies to justify a statistical treatment. Under these conditions the neutron angular distributions at the resonance energies are expected to be symmetric about $\theta_{c.m.} = 90°$. If a Hauser-Feshbach treatment of the fluctuation cross section is justified, then any contribution to the polarization from compound-nucleus events can be neglected and any resonance-like behavior of the polarization would indicate nonzero values for $M_{\lambda n}$. If the (p, n) reaction is dominated by its compound-nucleus part, then two open decay channels must exist[18] in order that the neutron polarization should not vanish. It is likely that analogs of other than the ground state of the parent nucleus need to be investigated in order to realize this condition. From an experimental point of view, it is important that the spacing of low-lying levels in the residual nucleus be such that at least a few of the individual final states can be resolved with present-day neutron-detection techniques.

Many of these conditions can perhaps be satisfied in (p, n) reaction studies on target nuclei in the neighborhood of $A = 90$. In this mass region, neutron angular distributions in analog-resonant (p, n) reactions appear to be symmetric about 90° and have been interpreted[19] to be primarily compound-nucleus processes. On the other hand, the neutron excess for nuclei in this mass region may be such that configuration states (or other simple states) make only a negligibly small contribution to the neutron decay to the ground state of the residual nucleus. This implies that information about possible mixing correlations can be obtained only by neutron polarization experiments to selected excited states of the final nucleus. As mentioned previously,[9] however, there is the possibility that the neighborhood of the analog may include other states that can mix with the analog and give rise to correlations that would be observable even in the neutron decay to the ground state.

ACKNOWLEDGMENTS

Useful discussions with Dr. A. M. Lane are gratefully acknowledged. We thank the authors listed in Ref. 14 for allowing us to use some of their data prior to publication.

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

[1]See, for example, D. Robson, in *Isospin in Nuclear Physics*, edited by D. H. Wilkinson (North-Holland, Amsterdam, 1969), p. 461; H. A. Weidenmüller, in *Nuclear Isospin*, edited by J. D. Anderson, S. D. Bloom, J. Cerny, and W. W. True (Academic, New York, 1969), p. 361.

[2]A. M. Lane, Phys. Lett. 29B, 263 (1969); A. M. Lane, in *Isospin in Nuclear Physics* (see Ref. 1), p. 509.

[3]See, for example, G. E. Mitchell, E. G. Bilpuch, J. D. Moses, W. C. Peters, and N. H. Prochnow, in *Statis-*

tical Properties of Nuclei, edited by J. B. Garg (Plenum, New York, 1972), p. 299; A. Richter, E. Grosse, J. Hüfner, and H. A. Weidenmüller, Phys. Lett. 38B, 349 (1972).

[4]C. Bloch, Nucl. Phys. 4, 503 (1957).

[5]D. Robson and A. M. Lane, Phys. Rev. 161, 982 (1967).

[6]C. Mahaux and H. A. Weidenmüller, Nucl. Phys. A130, 481 (1969).

[7]W. Hauser and H. Feshbach, Phys. Rev. 87, 366 (1952).

[8]T. Teichmann and E. P. Wigner, Phys. Rev. 87, 123 (1952).

[9]The configuration states provide one obvious source of correlation among the $T_<$ states. However, in the neighborhood of an analog state there may be other simple states that can mix with the fine structure and give rise to similar correlations. In fact, a recent calculation by A. Z. Mekjian [Phys. Rev. Lett. 25, 888 (1970)] indicates that the admixing of a $T=1$ monopole excitation of the core is a more important source of correlation for nuclei with mass number near $A=50$. For convenience, we continue to use the term configuration states to denote any such source of correlation among the $T_<$ states.

[10]See, for example, J. M. Blatt and L. C. Biedenharn, Rev. Mod. Phys. 24, 258 (1952); A. Simon and T. A. Welton, Phys. Rev. 90, 1036 (1953); H. L. Harney, Phys. Lett. 28B, 249 (1968).

[11]P. A. Moldauer, Phys. Rev. 135, B642 (1965).

[12]E. Teranishi and B. Furubayashi, Phys. Lett. 20, 511 (1966); E. Teranishi and B. Furubayashi, in *Isobaric Spin in Nuclear Physics*, edited by J. D. Fox and D. Robson (Academic, New York, 1966), p. 640.

[13]J. J. Egan, K. K. Sekharen, G. C. Dutt, J. E. Wiest, and F. Gabbard, Phys. Rev. C 5, 1562 (1972), and references therein.

[14]E. H. Sexton, A. J. Elwyn, F. T. Kuchnir, F. P. Mooring, J. F. Lemming, R. W. Finlay, and R. E. Benenson, Bull. Am. Phys. Soc. 16, 1432 (1971); and to be published.

[15]J. Catala, A. Garcia, J. M. Botta, S. Hinds, H. Marchant, and A. E. Forest, Nucl. Phys. 74, 1 (1965); J. H. Bjerregaard, P. F. Dahl, O. Hansen, and G. Sidenius, *ibid.* 51, 641 (1964).

[16]Because of the many parameters necessary for a complete specification of the channels, the available data are insufficient for an accurate treatment of each state in the theoretically more correct two-channel representation.

[17]K. K. Sekharen and M. K. Mehta, Phys. Rev. C 6, 2304 (1972).

[18]In those cases in which two entrance channels are coupled to the analog, similar information can be obtained from a measurement of the neutron asymmetry in a reaction initiated by polarized protons. H. J. Kim and R. L. Robinson [Nucl. Phys. A167, 73 (1971)] have observed entrance-channel interference effects in the angular distributions of the neutrons in the $^{91}Zr(p,n)$-^{91}Nb and $^{95}Mo(p,n)^{95}Tc$ reactions.

[19]E. Finckh, U. Jahnke, P. Pietrzyk, B. Schreiber, and A. Weidinger, Phys. Rev. C 1, 700 (1970); K. D. Büchs, E. Finckh, U. Jahnke, P. Pietrzyk, and B. Schreiber, in Contributions to Conference on Nuclear Structure with Neutrons, Budapest, 1972 (unpublished), p. 80.