INTERMEDIATE-STRUCTURE STRENGTH FUNCTION*

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Measurement of the two-particle one-hole or doorway-state strength function by suitable averaging of (d,p) and (p,p') cross section is proposed.

The structure exhibited by average proton or neutron elastic cross sections is well understood as due to a coherence of single-particle amplitudes in many levels of the compound nucleus. The single-particle strength function is obtained by measuring these average cross sections, and the bumps in the strength function correspond to single-particle resonances in the average nuclear potential.

In addition to single-particle structure, it has been proposed[1] that nuclear scattering should show intermediate structure of two-particle one-hole (2p-1h) character. The (2p-1h) states leading to this structure have been called doorway states.[2] [In these doorway states we include states consisting of a particle coupled to a collective mode with strong particle-hole component; for brevity we refer to these also as (2p-1h) levels.] In this paper we discuss the possibility of measuring the strength function[3] for these (2p-1h) states by combining data from (d,p) and (p,p') experiments. This strength function would give positions and widths of (2p-1h) levels, which could then be used in attempts to fit effective forces to nuclear structure.

We consider first the case $N=Z$, and use levels in the $A=41$ system as an example; the two experiments of interest are then $Ca^{40}(d,p)Ca^{41}$ and $Ca^{40}(p,p')Ca^{40}$. The (d,p) data of Belote, Sperduto, and Buechner[4] show both levels that give single-particle stripping angular distributions and those that do not. If there were data available for a very large number of levels in Ca^{41}, it would be possible to do a simple averaging of the (d,p) data in order to look for an intermediate structure modulation of the mainly single-particle cross section. However, the data are too sparse for that, so we cut down the background by simply throwing away all 34 levels that show a single-particle stripping pattern and then averaging the remaining 71 levels that lie in the region of excitation energies between 4.25 and 6.85 MeV. Fig. 1 shows a plot of

$$I\frac{d\sigma}{d\Omega}(E,I,30°)=\sum_{E'}{}'\frac{d\sigma}{d\Omega}(E',30°) \tag{1}$$

where $I=100$ keV, $E-\frac{1}{2}I\leq E'\leq E+\frac{1}{2}I$, and the prime on the summation sign is to show that single-particle levels are omitted. There are five likely candidates for (2p-1h) states in Ca^{41} evident in the figure. If we define

$$\alpha(I)=(\langle\sigma^2(E,I)\rangle-\langle\sigma(E,I)\rangle^2)/\langle\sigma(E,I)\rangle^2 \tag{2}$$

with the bracket denoting energy averaging over the entire 2.5-MeV interval, then a purely statistical picture of the level strengths [distribution $\propto\exp(-\sigma^2/\beta^2)$] and spacings (Poisson distribution), together with the assumption that any two levels are uncorrelated, gives

$$I\alpha(I)/D=1.274, \tag{3}$$

where D is the average level spacing. Figure 2 shows a plot of $I\alpha/D$ vs I for the Ca^{41} levels used in Fig. 1. The deviation from the value given by Eq. (3) occurs at about 100 keV and shows a coherence in the strengths or a correlation of levels involving levels in a region about 100 keV in width. This is consistent with the structures of Fig. 1 and indicates that they are not simply statistical fluctuations.

Of course, this does not show that these bumps are in fact intermediate structure of (2p-1h) character. A further test of their nature can be made by doing $Ca^{40}(p,p')$ with incident pro-

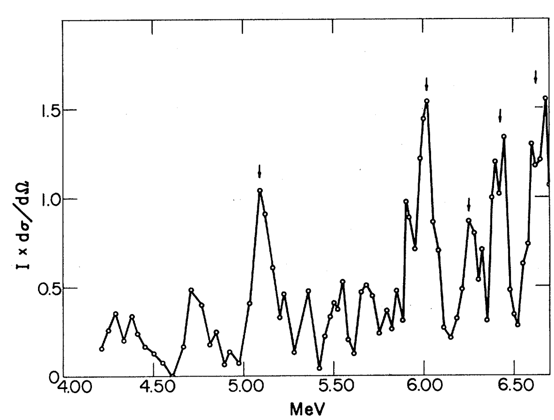

FIG. 1. The quantity $I(d\sigma/d\Omega)$ of Eq. (1) for $I=100$ keV, plotted as a function of E.

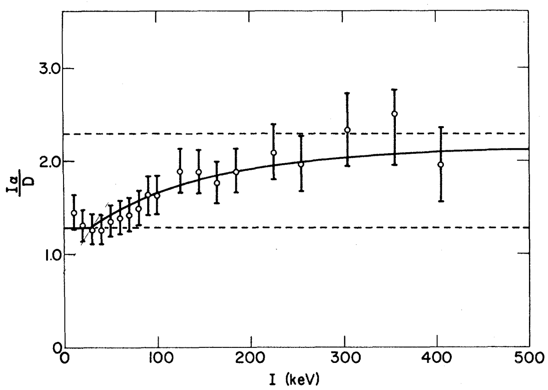

FIG. 2. $I\alpha(I)/D$ versus averaging interval I. The error bars are crude estimates assuming that the fractional error is $\sim N^{-1/2}$.

tons at the energy of the Sc^{41} "analog" of the suspected (2p-1h) state in Ca^{41} (when $T=\frac{1}{2}$, the analog is simply the mirror nucleus, but we call it the analog here because we discuss the case $N>Z$ later). The analogs of the bumps in Fig. 1 are in the region of protons of 3.5 to 5.5 MeV incident on Ca^{40}. If the Sc^{41} state really is a (2p-1h) state, then it should have a relatively large width for emitting a particle and leaving the Ca^{40} in a state of (1p-1h) character, i.e., a particle-hole state. More quantitatively, we expect that Γ_{ph}/Γ_g and therefore σ_{ph}/σ_g should be larger in the region of the (2p, 1h) analog than in the region of a single-particle analog, where ph and g refer to leaving the target in (1p-1h) excited state and ground state, respectively. In Ca^{40} there is a low-lying 3^- particle-hole state at about 3.5 MeV which can be used to test these states (except the first, which probably is too low to excite the 3^- strongly). The experiment is then to measure $\sigma_{3^-}(E)/\sigma_g(E)$ in $Ca^{40}(p,p')$ at energies corresponding to both analogs of single-particle states and analogs of the (2p-1h) candidates. A relatively large value of σ_{3^-}/σ_g indicates a strong (2p-1h) component.

Moreover, once the nature of the state is determined, the (p,p') experiment can give information about its spin and parity. The net result is that by combining (d,p) and (p,p'), we can get information about the (2p-1h) strength function like the information about the single-particle strength function that is obtained in the same experiments. Because the (2p-1h) strength is distributed over several Ca^{41} or Sc^{41} levels (about 8 each for the candidates in Fig. 1), it is necessary to do the averaging in such a way as to select the (2p-1h) component of these levels, just as the single-particle giant resonances show up in averaged (d,p) and averaged (p,p) cross sections when the averaging is done over ranges of the order of 1 MeV.

Consider now the situation when N is greater than Z; for concreteness we use $A=119$ as our example. The reactions of interest are $Sn^{118}(d,p)$ and $Sn^{118}(p,p')$. The (d,p) results can be analyzed as above to try to reveal the presence of (2p-1h) states in Sn^{119}. The $Sn^{118}(p,p')$ analysis seems more complicated, since the analogs of single-particle states in Sn^{119} are states in Sb^{119} that consist of only a small part of single-particle component [amplitude $(2T+1)^{-1/2}$] and are mostly (2p-1h) component [amplitude $\{2T/(2T+1)\}^{1/2}$], where $T=9$ is the isospin of Sn^{118}. (For $N=Z$, the analog of a single-particle state is a single-particle state, etc.) However, a simplification occurs because the <u>decay</u> of the analog of a single-particle state is mainly through its single-particle component,[5] so that the (p,p) resonance at the analog energy goes <u>through the single-particle component</u> of the analog state [although the width is narrowed by the factor $(2T+1)^{-1}$]. Similarly, the analog of a (2p-1h) state in Sn^{119} is a state in Sb^{119} that consists mainly of (3p-2h) component. However, the (p,p') experiment goes through the (2p-1h) component of this analog state, and therefore again the ratio σ_{ph}/σ_g is a measure of this (2p-1h) component of the analog state and, hence, of the (2p-1h) component of the original bump in the averaged (d,p) data. Just as in the case $N=Z$, the combination of (d,p) and (p,p') can be used to determine the (2p-1h) strength function. In Sn^{118} there are several (1p-1h) states available, with the 2^+ and 3^- collective states being the most useful. For $A=119$, the analogs of some single-particle $Sn^{118}(d,p)$ states[6] have been seen in $Sn^{118}(p,p)$ experiments and $Sn^{118}(p,p')$ experiments.[7] However, the $Sn^{118}(p,p')$ to the 2^+ and 3^- states in Sn^{118} shows more structure than is present in the old (d,p) experiment,[6] so there is a good possibility that a higher resolution (d,p) experiment might be able to give further information about the extra structure in the $Sn^{118}(p,p')$ data. The data of Ref. 7 show a number of resonances in $Sn^{118}(p,p')$ leaving collective 3^- and 2^+ excitations that are good candidates for analogs of (2p-1h) states in Sn^{119}, particularly in the regions of excitation of Sn^{119} between

0.8 and 1.4 and between 2.0 and 2.6 MeV. These structures can be due to several things, such as particle-vibration coupling, or noncollective (2p-1h) states. In order to distinguish among the various possibilities, it is essential to measure the spins of the resonances in proton scattering and also look at the (d, p) experiments to the corresponding regions in Sn^{119}. To separate noncollective (2p-1h) strength, it is necessary to measure inelastic scattering to noncollective particle-hole states in Sn^{118}.

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[1]A. K. Kerman, L. S. Rodberg, and J. E. Young, Phys. Rev. Letters 11, 422 (1963).

[2]B. Block and H. Feshbach, Ann. Phys. (N.Y.) 23, 47 (1963).

[3]The possibility of determining this strength function has also been discussed by J. E. Young and A. Zuker, to be published; and J. E. Young, to be published.

[4]T. A. Belote, A. Sperduto, and W. W. Buechner, Phys. Rev. 139, 880 (1965).

[5]See the discussion of this point in A. F. R. deToledo Piza, thesis, Massachusetts Institute of Technology, 1966 (unpublished); and also A. F. R. deToledo Piza and A. K. Kerman, to be published.

[6]B. L. Cohen and R. E. Price, Phys. Rev. 121, 1441 (1961).

[7]D. L. Allan, G. A. Jones, G. C. Morrison, R. B. Taylor, and R. B. Weinberg, Phys. Letters 17, 56 (1965).

PHENOMENOLOGICAL ANALYSIS OF CP NONINVARIANCE IN $K^{\pm} \to 3\pi$ DECAY*

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We analyze the effect of CP noninvariance in the decay $K^{\pm} \to 3\pi$ under the assumption that the violation of CP invariance, first observed by Christenson et al.,[1] occurs in the weak interactions.[2] It has been pointed out[3,4] that the violation of CP invariance may produce a difference between the Dalitz plots and partial rates for $K^{+} \to 3\pi$ and its CPT conjugate state; if CPT invariance is valid, these effects also require the existence of strong final-state interaction between the pions.[5] The following analysis differs from a previous calculation by Ueda and Okubo[3] in that (a) we use a different parametrization of the CP nonconserving effect, and (b) a pure $I=1$ final state is not assumed. We shall examine in some detail the possibility of testing CP noninvariance with $\Delta I > \frac{1}{2}$ as suggested earlier.[6,7]

We analyze the τ and τ' decays in terms of the four independent isospin states of three pions which can contribute to a matrix element linear in the energy of the odd pion. Assuming CPT invariance, we write

$$M(\tau^{\pm}) = 2\lambda \exp(i\delta_{\lambda} \pm i\varphi_{\lambda}) + b \exp(i\delta_{b} \pm i\varphi_{b})(s_3 - s_0)/\mu^2 + c \exp(i\delta_{c} \pm i\varphi_{c})(s_3 - s_0)/\mu^2 + d \exp(i\delta_{d} \pm i\varphi_{d}), \quad (1)$$

$$M(\tau'^{\pm}) = -\lambda \exp(i\delta_{\lambda}' \pm i\varphi_{\lambda}) + b \exp(i\delta_{b}' \pm i\varphi_{b})(s_3 - s_0)/\mu^2 - c \exp(i\delta_{c} \pm i\varphi_{c})(s_3 - s_0)/\mu^2 + 2d \exp(i\delta_{d} \pm i\varphi_{d}), \quad (2)$$

where $s_i = (P_K - P_i)^2 = (m-\mu)^2 - 2mT_i$, $i = 1, 2, 3$, and the index 3 refers to the odd pion; the symmetry point is $s_0 = \frac{1}{3}(s_1 + s_2 + s_3)$, T_i is the kinetic energy of the ith pion in the rest frame of the K meson, and m and μ are, respectively, the K and π masses. The δ are the phase shifts due to strong (CP-conserving) pion-pion interaction, the φ are the CP-nonconserving phases, assumed for simplicity to be independent of the