Single-particle protons widths of isobaric analog resonances

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A formula is proposed, on the basis of the shell model, for single-particle proton widths of isobaric analog resonances; this formula takes into account the approximate conservation of the isospin. It is shown that calculations by this formula are stable against variations of the parameters of the model.

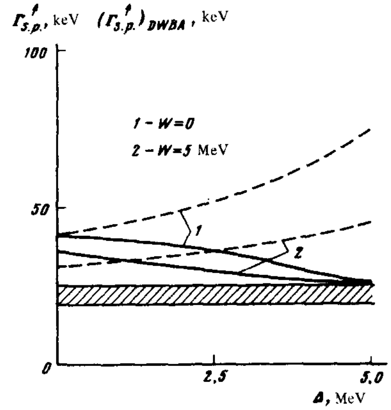
One of the important practical purposes of the theory of isobaric analog resonances (IAR) is the derivation of a formula for the single-particle proton width $\Gamma^{\dagger}_{s.p.}$ of the IAR. The main difficulty encountered by the microscopic approaches to the description of IAR is the allowance for the influence of complicated configurations on the formation of the IAR, and in particular on the value of $\Gamma^{\dagger}_{s.p.}$. This influence can be taken into account within the framework of a phenomenological approach in which the "nucleon + target nucleus" system is described by using the following Hamiltonian[1]

$$H = K + \bar{U} + \mathbf{t}\mathbf{T}\bar{V} + \left(\frac{1}{2} - t^{(3)}\right)V_C \quad , \tag{1}$$

where K is the kinetic energy, $\bar{U}$ and $\bar{V}$ are the effective values of the isoscalar and isovector potentials, and V_c is the Coulomb energy. The requirements imposed on this Hamiltonian are, first, that it go over for the "neutron in bound state + target nucleus" system into the shell-model Hamiltonian $h_n = K + U + T_0V/2$, and second, that for the "proton in the continuous spectrum + target nucleus" system it go over into the optical-model Hamiltonian for protons, $h_n = K + U - T_0V/2 + V_c - iW + \Delta$. These two requirements lead to the following expression for the Lane effective potential (or for the effective symmetry energy) $T_0\bar{V} = T_0V + iW - \Delta$, where T_0 is the target-nucleus isospin. The proton width of the IAR is due to the coupling between the input state $|d\rangle = |nA\rangle(|A\rangle \sim T^{(-)}|0\rangle$ is the analog of the target nucleus and $|n\rangle$ is the single-neutron state of the parent nucleus) and the proton state of the continuous spectrum. Allowance for this coupling, which is due to the isovector part of the Hamiltonian (1), leads to the following expression for the width $\Gamma^{\dagger}_{s.p.}$:

$$\Gamma^{\dagger}_{s.p.} = (2T_0 + 1)^{-1} 2\pi \left| \int \chi_E T_0 V \chi_n \, dr \right|^2 \quad , \tag{2}$$

where χ_E and χ_n are the radial wave functions of the protons and neutrons. This expression differs from the



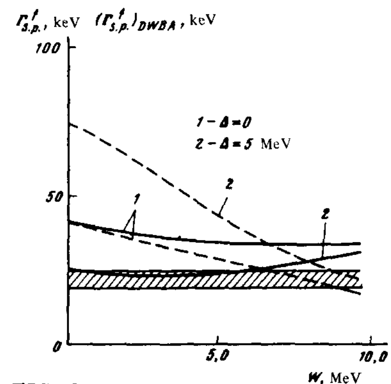


FIG. 2.

FIGS. 1 and 2. Plots of the widths $\Gamma^{\dagger}_{s.p.}$ (solid lines) and $(\Gamma^{\dagger}_{s.p.})_{DWBA}$ (dashed lines) for the $g_{9/2}$ IAR (the reaction ^{208}Pb (p, p_0); the resonance energy is $E_r = 14.9$ MeV) against W and Δ *in the case of volume absorption. Similar plots are obtained* in the case of surface absorption. The shaded strip marks the region of experimental values of the width $\Gamma^{\dagger}$.

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quantities V and h_p is taken into account. Plots of the width (2) against the parameters W and Δ, using as an example the IAR $g_{9/2}$ excited in the reaction $Pb^{208}(p, p_0)$, are shown in Figs. 1 and 2. As expected on the basis of the structure of formula (2), the dependence on the "shift" Δ turns out to be stronger than on the value of W.

The phenomenological approach leaves the following questions unanswered: 1) how should the symmetry energy $T_0 V$ be chosen? 2) what is the physical meaning of the effective symmetry energy $T_0 \bar{V}$ in formula (2)? Answers to these questions can be obtained on the basis of the shell approach in the theory of nuclear reactions, in which the bound states in a reaction with nucleons are treated by a unified approach. We note that allowance for the excitation of complicated configurations in elastic scattering of nucleons by nuclei leads within the framework of the shell approach to the same parametrization of the average S matrix as the optical model.[2] These factors enable us to establish a connection between the microscopic and phenomenological approaches.

The first of the posed questions is of practical significance. Thus, the transition from the volume potential V to a surface potential nearly doubles the width $\Gamma'_{s.p.}$.[1] The shell approach, within the framework of which the analog states can be interpreted as collective 0^+ excitations of the proton-neutron hole type, leads to the following result: $T_0 V = F' n(r)$. Here F' is the intensity of the charge-exchange part of the quasiparticle interaction and $n(r)$ is the effective density of the excess neutrons. The difference that this interaction produces between the effective density and the single-quasiparticle density $n_0(r)$ due to the "core" polarization can be approximately taken into account by the formula

$$n(r) = (1 + f')^{-1}[n_0(r) + f'\bar{n}(r)], \qquad (3)$$

where $\bar{n}(r)$ is a Woods-Saxon distribution normalized to the neutron excess and $f' = 1.3 \pm 0.3$ is the dimensionless value of the force constant F'. The uncertainty in the choice of this constant has little effect on $\Gamma'_{s.p.}$. This statement is illustrated in Fig. 3 with the above-considered IAR as an example.

Formula (2) can be obtained on the basis of the shell approach to the description of the IAR. In the energy interval near the IAR, the complicated states $|\lambda\rangle$ are characterized by a "normal" isospin $T_< = T_0 - 1/2$. There is therefore no connection between them and the analog state $|a\rangle$ with isospin $T_> = T_0 + 1/2$, owing to the "residual" nuclear interaction H', i.e., $\langle a|H'|\lambda\rangle = 0$ ($|a\rangle \approx |d\rangle + (2T_0)^{-1/2}$ and $|p\rangle$ is a single-proton state with the same spatial configuration as the state $|n\rangle$).

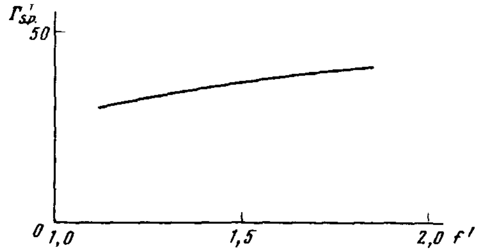

FIG. 3. Dependence of the width $\Gamma'_{s.p.}$ on f' for the indicated IAR in the case $W = \Delta = 0$ (this dependence becomes weaker for realistic values of W and Δ). The shell-parameter models are taken from the monograph.[3]

This condition leads to the following equations, on which the derivation of formula (2) is based:

$$\sum_\lambda \frac{\langle d|H'|\lambda\rangle\langle\lambda|H'|E\rangle}{E - E_\lambda + iI} = -\frac{1}{\sqrt{2T_0}}\sum_\lambda \frac{\langle p|H'|\lambda\rangle\langle\lambda|H'|E\rangle}{E - E_\lambda - iI} = \frac{1}{\sqrt{2T_0}}\int \chi_n(iW - \Delta)\chi_E^{opt}\,dr, \qquad (4)$$

where I is the averaging interval. Thus, the effective symmetry energy in formula (2) is the result of allowance for the approximate isospin conservation. The assumption, natural at first glance, that the phase shifts of the matrix elements $\langle d|H'|\lambda\rangle$ and $\langle\lambda|H'|E\rangle$ are random, turns out to be incorrect in the case of IAR. This assumption, used in most microscopic approaches to the description of the IAR, leads in accordance with (4) to an expression for the single-particle proton width, which is obtained from formula (2) by the substitution $\bar{V} \to V$. The corresponding width, which should naturally be designated $(\Gamma'_{s.p.})_{DWBA}$, reveals a much stronger dependence on the optical-model parameters W and Δ than the width $\Gamma'_{s.p.}$ (see Figs. 1 and 2).

The stability of the widths $\Gamma_{s.p.}$ against the parameter variations considered above is the consequence of the self-consistent calculation method: the same quantities W, Δ, and V determine the widths (2) both directly and in terms of the nucleon wave functions. We can therefore count on being able to determine in practice the absolute values of the spectroscopic factors of low excited states of nuclei from the experimental values of the IAR proton widths.

[1]H. Bledsoe and T. Tamura, Nucl. Phys. **A164**, 191 (1971).
[2]M.G. Urin, Obolochechnye éffekty v rezonansynkh yadernykh reaktsiyakh s nuklonami (Shell Effects in Resonant Nuclear Reactions with Nucleons), Moscow, MIFI, 1974.
[3]P. É. Nemirovskiĭ, Sovremennye modeli atomnogo yadra (Modern Models of the Atomic Nucleus), Moscow, Atomizdat, 1960.