Direct neutron decay of isobaric analog resonances

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(Submitted January 20, 1975)
ZhETF Pis. Red. **21**, No. 6, 386–388 (March 20, 1975)

An interpretation of the isospin-forbidden direct neutron decay of isobaric analog resonances (IAR) is proposed on the basis of the shell model. A formula is obtained for the elastic IAR neutron width. The concrete calculations were performed for the case of neutron scattering by the nuclei ^{90}Zr and ^{206}Pb.

The study of isospin-forbidden reactions with excitation of IAR leads to conclusions both concerning the mechanism of the reaction and the mechanism whereby the isospin symmetry of isobaric analog states (IAS) is destroyed. Among the indicated reactions is included the excitation of IAR by neutrons ($\Delta T = 3/2$). The direct neutron decay of IAR is characterized by partial neutron widths $\Gamma_n^{\uparrow}$ and determines the hard part of the neutron spectrum. The first experimental indications of excitation of IAR by neutrons were published recently. [1,2]

A simple quantitative interpretation of the destruction of isospin symmetry of IAS on account of the average Coulomb field $V_C(r)$ can be obtained within the framework of the one-particle model. The correction to the wave function (WF) of the IAS, necessitated by this field as a result of the elastic proton channel of the IAR decay (on account of the so-called "external" mixing) can be represented, accurate to within a weighting factor, in the form[3]

$$\delta\chi_j(r) = -\int G_{Ej}^{(+)}(r, r')v(r')\chi_j(r')dr' - \chi_j(r). \qquad (1)$$

Here $\chi_j(r)$ is the radial WF of the "valent" neutron in the parent nucleus: $(h_n(r) - \epsilon_n)\chi_j(r) = 0$, where $h_n(r) = K + U + (1/2)v$ is the Hamiltonian of the shell model for the neutrons; $G_{Ej}^{(+)}(r, r')$ is the Green's function of the radial Schrödinger equation $(h_p(r) - E)G_{Ej}^{(+)}(r, r') = \delta(r - r')$, where $h_p(r) = K + U - (1/2)v + V_C(r)$ is the shell-model Hamiltonian for protons; K is the kinetic energy; U is the isoscalar part of the shell potential; v is the symmetry energy; and E is the IAR energy in the proton channel.

To the extent of the correction (1), a direct neutron decay of the IAR is possible on account of the nuclear interaction $\hat{F}$. We choose the parametrization of the effective interaction in the particle-hole channel to be the same as in the theory of finite Fermi systems[4]:

$$\hat{F} = C[f(\mathbf{r}_1) + f'(\mathbf{r}_1)\vec{\tau}_1\vec{\tau}_2 + \vec{\sigma}_1\vec{\sigma}_2(g(\mathbf{r}_1) + g'(\mathbf{r}_1)\vec{\tau}_1\vec{\tau}_2)]\delta(\mathbf{r}_1 - \mathbf{r}_2). \qquad (2)$$

Here $f(\mathbf{r}) = f_{ex} + (f_{in} - f_{ex})f_{WS}(\mathbf{r})$ etc., where $f_{WS}(\mathbf{r})$ is a Woods-Saxon distribution, $f_{ex}^{nn} = (f + f')_{ex}$ etc. are phenomenological constants, and $C = 380$ MeV-F^3.

Resonant scattering of neutrons by a magic nucleus (Z, N) with isospin T_0 excites in the nucleus $(Z, N+1)$ an analog of the parent nucleus $(Z-1, N+2)$ with isospin $T_0 + 3/2$. We consider the simplest configurations of the parent nucleus $[\{j'(p)\}^{-1}, [j(n)]^2_{0+}\}$. In this case the amplitude of the direct neutron decay is determined by the sum of diagrams that correspond respectively to the non-exchange and charge-exchange parts of the effective interaction of the neutron with the proton (2) (see the figure). A direct calculation based on relations (1) and (2) leads to the following formula for the elastic neutron width $\Gamma_n^{\uparrow}$:

$$\Gamma_n^{\uparrow} = \frac{C^2}{16\pi}\frac{2j+1}{2T_0+3}\left|\int(f^{nn} - 3g^{nn})\delta\chi_j\chi_j\chi_{j'}\chi_{E'j'}r^{-2}dr\right|^2, \qquad (3)$$

where $\chi_{j'}(r)$ is the radial WF of the proton hole in the parent nucleus (eigenfunction of the Hamiltonian h_p), and $\chi_{E'j'}(r)$ is the radial WF, normalized to an energy δ-function, of the continuous spectrum for neutrons (eigenfunction of the Hamiltonian h_n). Since we ignored in the derivation of (3) the possibility of excitation of complex configurations in the process of the direct neutron decay of the IAR, the width $\Gamma_n^{\uparrow}$ can be called the "natural" width.

The influence of complex configurations on the effective elastic neutron width of IAR must be taken into account in two cases: a) the WF of the continuous spectrum for neutrons, $\tilde{\chi}_{E'j'}$, is determined with the aid of the optical-model Hamiltonian $h_n = h_n + \Delta_n - iw_n$; b) the effective correction to the WF of IAS is determined with allowance for excitation of complex configurations in the process of elastic scattering of the protons[3]:

$$\delta\tilde{\chi}_j = \delta\chi_j - \int G_{Ej}^{(+)}(r, r')[\Delta_p(r') - iw_p(r')]\delta\tilde{\chi}_j(r')dr' \qquad (4)$$

Thus, the effective neutron width $\tilde{\Gamma}_n^{\uparrow}$ is determined by formula (3), in which we make the substitutions $\chi_{E'j'} \to \tilde{\chi}_{E'j'}$ and $\delta\chi_j \to \delta\tilde{\chi}_j$. A measure of the purity of the IAS isospin for the considered process can be taken to be the ratio $\Gamma_n^{\uparrow}/[\tilde{\Gamma}_n^{\uparrow}]$, where the width $[\Gamma_n^{\uparrow}]$ is determined without allowance for the isospin conservation, i.e., by expression (3), in which the correction $\delta\tilde{\chi}_j$ is formally replaced by the function χ_j.

Formulas (3) and (4) were used to calculate the widths $\tilde{\Gamma}_n^{\uparrow}$, and also the width ratios $\Gamma_n^{\uparrow}/[\tilde{\Gamma}_n^{\uparrow}]$ for the case of neutron scattering by the nuclei ^{90}Zr and ^{206}Pb with excitation of analogs of proton-hole states of the parent nuclei ^{91}Y and ^{207}Tl, respectively. The choice of the indicated nuclei is due to two factors: 1) the elastic width $\tilde{\Gamma}_n^{\uparrow}$ is determined by the simplest formula; 2) in this nuclear region, one investigates experimentally the excitation of IAR by neutrons. [1,2] The resonant energies E' were determined either from the experimental data or by calculation. In the calculations we used the fol-

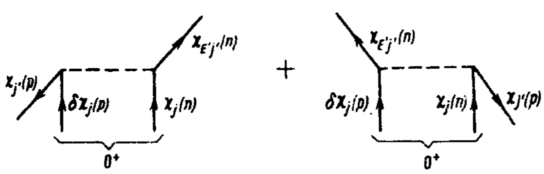

FIG. 1.

TABLE I. The result of the calculation of the widths $\tilde{\Gamma}'_n$, the hindrance factors $\tilde{\Gamma}'_n/[\tilde{\Gamma}'_n]$, and the quantities $(j'+1/2)\tilde{\Gamma}'_n$ that characterize the cross sections of resonant reactions at the maximum.

Target nucleus	^{90}Zr ($j_n^\pi = 5/2^+$)						^{206}Pb ($j_n^\pi = 1/2^-$)		
j'^π	$1/2^-$	$9/2^+$	$3/2^-$	$5/2^-$	$7/2^-$	$5/2^+$	$1/2^+$	$3/2^+$	$5/2^+$
E', MeV	5.21	5.63	5.72	6.15	6.39	6.48	12.8	13.1	14.4
$\tilde{\Gamma}'_n$, keV	1.48	0.07	1.40	0.53	0.33	1.66	0.62	0.11	0.08
$\tilde{\Gamma}'_n/[\tilde{\Gamma}'_n]$	0.14	0.15	0.14	0.14	0.16	0.13	0.41	0.13	0.11
$(j'+1/2)\tilde{\Gamma}'_n$, keV	1.48	0.37	2.80	1.59	1.32	4.98	0.62	0.22	0.24

lowing values of the shell and optical-potential parameters: $U=-52$ MeV, $v=55(N-Z)A^{-1}$ MeV, $a=0.63$ F, $r_0=r_C=1.245$ F, $V_{ls}=7.5$ MeV, $\Delta_{p,n}=0.33E_{p,n}$ MeV, $w_p=7.5$ MeV, $w_n=6$ MeV (surface absorption). The values of the force constants were taken from[5]: $f_{in}^{nn}=0.4$, $f_{ex}^{nn}=-1.7$, and $g_{in}^{nn}=g_{ex}^{nn}=1.3$, so that the spin part of the interaction makes the main contribution to the width $\tilde{\Gamma}'_n$. The results of the calculation (table) permit the following conclusions to be made: 1) the isospin hindrance of the direct neutron decay of IAR is not too strong; the quantity $(j'+1/2)\tilde{\Gamma}'_n$ constitutes a noticeable fraction of the total width for relatively light nuclei. This statement does not contradict the experimental data.[2]

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