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STRUCTURE OF THE ISOBAR ANALOG STATES (IAS), DOUBLE ISOBAR-ANALOG STATES (DIAS), AND CONFIGURATION STATES (CS) IN HALO NUCLEI

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Структура изобар-аналоговых (IAS), дубль-аналоговых (DIAS)
и конфигурационных (CS) состояний
в голоидальных ядрах

Обсуждается структура возбужденных состояний и резонансов с различным изоспином в галоидальных ядрах. Показано, что волновые функции изобар-аналоговых, дубль-аналоговых и конфигурационных состояний могут одновременно содержать компоненты, соответствующие nn, np и pp гало.

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Structure of the Isobar Analog States (IAS),
Double Isobar-Analog States (DIAS), and Configuration States (CS)
in Halo Nuclei

Structure of the excited states and resonances with different isospin quantum numbers in halo-like nuclei is discussed. It is shown that isobar analog, double isobar-analog, and configuration states can simultaneously have nn, np, and pp halo components in their wave functions.

The investigation has been performed at the Flerov Laboratory of Nuclear Reactions, JINR.

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INTRODUCTION

The isobar analog state (IAS) of the halo nuclei may also have a halo-like structure [1]. In [2] it is shown that the IAS of the ^{6}He ground state (neutron halo nucleus), i.e., the 3.56 MeV 0^+ state of ^{6}Li, has a neutron–proton halo structure.

In the general case [3], the IAS is the coherent superposition of the excitations like neutron hole–proton particle coupled to form the momentum $J = 0^+$. The IAS has the isospin $T = T_Z + 1 = (N - Z)/2 + 1$. The isospin of the ground state is $T = T_Z = (N - Z)/2$. When the IAS energy corresponds to the continuum, the IAS can be observed as a resonance. Configuration states (CS) are not the coherent superposition of such excitations and have $T = T_Z = (N - Z)/2$. The CS formation is restricted by the Pauli principle.

The double isobar-analog state (DIAS) has the isospin $T = T_Z + 2$ and is formed as the coherent superposition of the excitations like two neutron holes–two proton particles coupled to form the momentum $J = 0^+$.

For the IAS, CS, and DIAS, the proton particles have the same spin and spatial characteristics as the corresponding neutron holes. When the parent state is a two-neutron halo nucleus, IASs and CSs will have the proton–neutron halo structure, DIASs and the double configuration states (DCSs) will have the proton–proton halo structure. For nuclei with enough neutrons excess, IASs and CSs can have not only the pn-halo component but also the nn-halo component, DIASs and DCSs can have both pp, nn, and pn components. IASs, CSs, and DIASs can be observed as resonances in nuclear reactions.

1. ISOBAR ANALOG STATES, DOUBLE ISOBAR-ANALOG STATES, AND CONFIGURATION STATES

Analog states in nuclei are of interest for both theoretical and experimental investigations. There are two main points that are decisive for the isospin T being a good quantum number in both light and heavy nuclei.

1. Charge independence of nuclear forces acting between nucleons.

2. A number of factors that weaken violation of the charge independence of forces in a nucleus by the Coulomb forces.

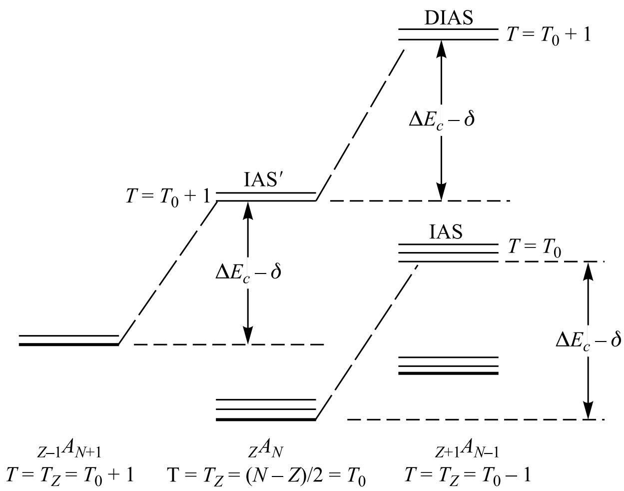

Fig. 1. Diagram of analog and double analog states

As a result, in a nucleus there can be (Fig. 1) several systems of levels (resonances) that differ in isospin $T(T_0, T_0 + 1, \ldots), T_0 = (N - Z)/2$. If $T = T_Z + 1$, these are the so-called analog states; if $T = T_Z + 2$, these are double analog states, and so on. Analog states that fall within the continuum region are also referred to as analog resonances. Analog states are formed from the initial state $(T, T = T_Z)$ through various replacements of a neutron by a proton in the same state. The wave function of the analog involves excitations like proton particle–neutron hole coupled to form the momentum $J = 0^+$ which are not forbidden by the Pauli principle. Levels with the identical T are in the neighboring nuclei and are shifted relative to each other by $\Delta E_c - \delta$, where ΔE_c is the Coulomb energy of the added proton and δ is the mass difference of the neutron and the proton.

The analog structure can be obtained by applying the operator

$$T_- = \sum \alpha_i^+(p)\alpha_i^-(n), \tag{1}$$

and the double analog structure is obtained by twice applying the nucleus isospin ladder operator T_- to the ground state of the parent nucleus. T_- is the operator for transformation of the neutron to the proton without a change in the function of the state in which the particle is; i.e., in (1) $\alpha_i^-(n)$ is the operator for annihilation of the neutron in the state i, and $\alpha_i^+(p)$ is the operator for production of the proton in the state i. By virtue of the Pauli principle, the summation is limited to the states which are filled with the excess neutrons.

The wave function of the analog state is written as

$$\psi^{\mathrm{IAS}}_{T_0+1,\,T_0} = \frac{1}{\sqrt{2(T+1)}} T_- \psi^{\mathrm{PS}}_{T_0+1,\,T_0+1}. \tag{2}$$

Here $\psi^{\mathrm{PS}}_{T_0+1,\,T_0+1}$ is the wave function for the parent states with the isospin $T = T_0 + 1$ and the isospin projection $T_Z = T_0 + 1$ (Fig. 1). The analog state turns out to be sharply distinguished in many properties because its isospin is greater by one than the isospin of the neighboring states. The experimental and theoretical data indicate that the mixing of states with different isospins is insignificant and the individual character of analog states distinctly manifests itself in many experiments.

For nuclear ground states, the isospin is equal to the isospin projection $T = T_Z = (N - Z)/2$. The analog state differs in isospin by one from the neighboring states, and the isospin of the analog state is greater by one than the isospin projection $T = T_Z + 1$. For the double analog state $T = T_Z + 2$.

The analog state is a collective state, which is coherent superposition of elementary excitations like proton particle–neutron hole coupled to form the momentum $J = 0^+$, i.e., all elementary excitations enter into the wave function of the analog with one sign (Fig. 2). Accordingly, the double analog state is coherent superposition of elementary excitations like two protons–two neutron holes coupled to form the momentum $J = 0^+$.

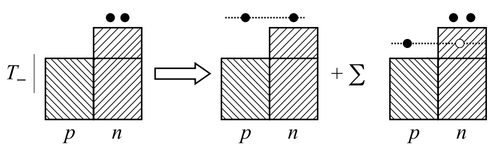

Fig. 2. Structure of the IAS wave function when the parent state has the nn halo. The analog wave function involves two components corresponding to the pn and nn halo

If the elementary excitations enter into the wave function incoherently, the so-called configuration states are formed. In halo-like nuclei formation of configuration states can be associated with core excitation, and in some case it can be forbidden by the Pauli principle. The isospin of the configuration states is smaller

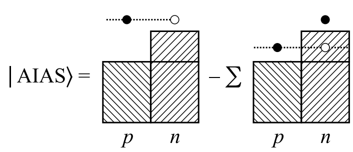

Fig. 3. Structure of the AIAS wave function when the parent state has the n halo. The antianalog wave function involves two components corresponding to the p and n halo

than the analog isospoin by one, and the excitation energy of the configuration states is also lower than the analog excitation energy. One of the best studied configuration states is (Fig. 3) the antianalog state (AIAS).

Since transformation of the neutron to the proton during the formation of analog, double analog, and configuration states is not followed by a change in the spatial and spin characteristics, the above-excited states in the halo-like nuclei will also have a halo-like structure.

2. HALO STRUCTURE FOR THE ANALOG, DOUBLE ANALOG, AND CONFIGURATION STATES

Let us take as the parent state the wave function for the ground state of the nucleus in which two neutrons make up the nuclear halo (nn halo) and act on it by the operator T_- (Fig. 2). As a result, we find that the wave function for the analog state and configuration states involves components corresponding to the proton–neutron halo (np halo) and two-neutron halo (nn halo). For some nuclei, configuration states are not formed by virtue of the Pauli principle, and the analog wave function can lack the component corresponding to the nn halo.

Let us act by the operator T_- on the ground-state wave function for the nn halo nucleus once more (Fig. 4).

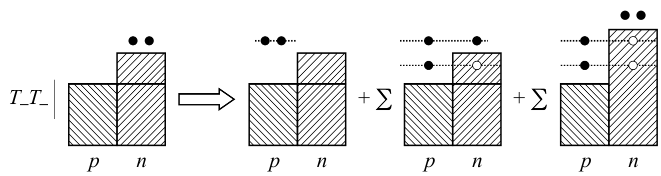

Fig. 4. Structure of the DIAS wave function when the parent state has the nn halo. The double analog wave function involves three components corresponding to the pp, pn, and nn halo

We find that the wave function for the double analog state and configuration states has the components corresponding to the pp, pn, and nn halo. For some nuclei, there can be no pn and nn halo components by virtue of the Pauli principle.

Let us consider a few examples.

^{6}**He nucleus (*nn* halo).** Two neurons that form the nn halo occupy the $1p$ orbit. The remaining two neutrons and two protons occupy the $1s$ orbit. Therefore, the action of the operator T_- on the ground-state wave function for the ^{6}He nucleus ($T = 1, T_z = 1$) results in the formation of the analog state with the configuration corresponding to the pn halo. This analog state is in the ^{6}Li nucleus ($T = 1, T_z = 0$) at the excitation energy 3.56 MeV. The width of this state is $\Gamma = 8.2$ eV, which corresponds to the half-life $T_{1/2} = 6 \cdot 10^{-17}$ s. The experimental data $[2, 6, 7]$ indicate that this state has a pn halo. Formation of configuration states is prohibited by the Pauli principle.

A repeated action of the operator T_- on the ground-state wave function for the ^{6}He nucleus results in the formation of the double analog resonance, which manifests itself in the unstable isotope ^{6}Be. This resonance should have pp halo structure, and it corresponds to the ^{6}Be ground state $(T = 1, T_z = -1)$. The width of this resonance is known to be $\Gamma = 92$ keV, which corresponds to $T_{1/2} = 5 \cdot 10^{-21}$ s. This resonance is a good candidate for observation of the two-proton decay. Formation of configuration states is also forbidden by the Pauli principle.

^{11}Li nucleus (nn halo). Two neutrons that form the nn halo occupy the $2s$ and $1p$ orbits. The ^{11}Li ground-state wave function has the form

$$\begin{gathered} ||\Psi(^{11}\mathrm{Li})\rangle \approx ||\Psi(^{9}\mathrm{Li}) \otimes 2n\rangle, \\ ||\Psi(^{9}\mathrm{Li}) \otimes 2n\rangle \approx a_s||\Psi(^{9}\mathrm{Li}) \otimes (2s_{1/2})^2\rangle + a_p||\Psi(^{9}\mathrm{Li}) \otimes (1p_{1/2})^2\rangle. \end{gathered} \tag{3}$$

The action of the operator T_- on the ^{11}Li ground state ($T = 5/2$, $T_z = 5/2$) results in the formation of the analog resonance in the ^{11}Be nucleus ($T = 5/2$, $T_z = 3/2$) with the excitation energy 21.08 MeV, which has both the nn and pn halo structure. That means that the wave function of this analog state (Fig. 2) has two components, one of which is associated with the pn halo and the other with the nn halo. A repeated action of the operator T_- on the ^{11}Li ground state $(T = 5/2, T_z = 5/2)$ gives us the double analog resonance which is in the ^{11}B nucleus $(T = 5/2, T_z = 1/2)$ at the excitation energy 33.58 MeV. The wave function of this double analog state will have three components corresponding to the nn, pn, and pp halo (Fig. 4).

Here formation of configuration states is not prohibited either under single or double action of the operator T_- on the ^{11}Li ground state. The configuration states will have lower excitation energy than the analog resonance arising from the single action of the operator T_- and the double analog resonance arising from the double action of the operator T_-. The structure of the configuration states will correspond to the pn and nn halo at the single action of the operator T_-. At the double action of the operator T_- the structure of the configuration states will correspond to the nn, pn, and pp halo. Evaluation of the configuration state energies is a more difficult problem than evaluation of the analog and double analog state energies. Energies of configuration states strongly depend on the nuclear model used.

^{11}Be nucleus (n halo). It is considered to be an established fact that the ^{11}Be nucleus has a one-neutron halo (n halo) [6, 7]. The action of the operator T_- on the ^{11}Be ground state $(T = 3/2, T_z = 3/2)$ results in the formation of the analog resonance in the ^{11}B nucleus $(T = 3/2, T_z = 1/2)$ with the excitation energy $E_{\mathrm{IAS}} = 12.56$ MeV. The wave function of this analog resonance will have two components corresponding to the n halo and p halo. Formation of configuration states is not prohibited by the Pauli principle. The energy of one of the configuration states (antianalog state) E_{AIAS} in ^{11}B ($T = 1/2, T_z = 1/2$) can be evaluated using [3] the relation

$$E_{\mathrm{IAS}} - E_{\mathrm{AIAS}} \approx (2T+1) \cdot \frac{V}{A}, \quad V \approx 100 \text{ MeV}. \tag{4}$$

The antianalogue state is in the ^{11}B nucleus at the excitation energy of about 3.5 MeV and has the structure of both the n halo and the p halo.

On the repeated action of the operator T_- on the ^{11}Be ground state we obtain the double analog resonance in the ^{11}C nucleus ($T = 3/2, T_z = -1/2$) at the excitation energy 12.16 MeV. The wave function for the double analog resonance in ^{11}C has components corresponding to the n halo and p halo.

CONCLUSIONS

1. Such excited states and resonances as isobar analog, double isobar analog, and configuration states in halo nuclei can also have a halo-like structure of different types (nn, pp, pn).

2. Isobar analog, double isobar analog, and configuration states can simultaneously have nn, np, and pp halo components in their wave functions.

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