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

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Structure of the excited states and resonances with different isospin quantum numbers in halolike nuclei is discussed. It is shown that IAS, DIAS, and CS can simultaneously have nn, np, and pp halo components in their wave functions

1. Introduction

The isobar analogue state (IAS) of the halo nuclei may also have a halolike structure [1]. In [2] it is shown that the IAS of the ^{6}He ground state (nn halo nucleus), i.e., the 3.56 MeV 0^+ state of ^{6}Li, has a np halo structure. The IAS [3] is the coherent superposition of the excitations like neutron hole–proton particle coupled to form the momentum $J=0^+$. The IAS has the isospin $T=T_z+1$. 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 $T=T_z$. The CS formation is restricted by the Pauli principle. The double isobar analogue 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.

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2. IAS, DIAS, and CS

Analogue states (analog) 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 Coulomb forces.

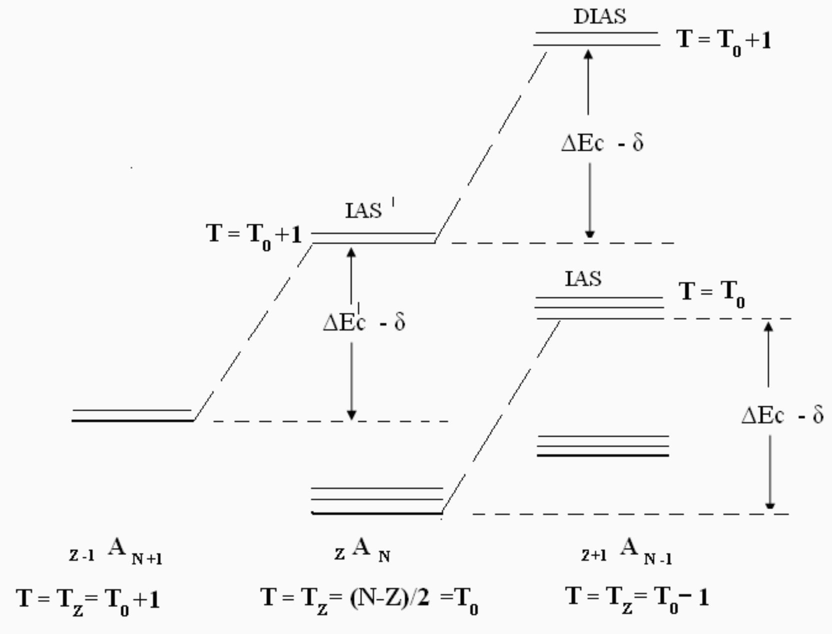

Figure 1. Diagram of analogue and double analogue states.

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 so-called analogue states (IAS); if $T=T_Z+2$, these are double analogue states (DIAS), and so on. IAS that fall within the continuum region are also referred to as analogue resonances. IAS 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 [3] 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 $\boldsymbol{T_-}$and the double analog structure is obtained by twice applying the nucleus isospin ladder operator $\boldsymbol{T_-}$ to the ground state of the parent nucleus. $\boldsymbol{T_-}$ 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 [3]. For nuclear ground states the isospin is equal to the isospin projection $T=T_Z=(N-Z)/2$. The IAS differs in isospin by one from the neighboring states, and the isospin of the IAS is greater by one than the isospin projection $T=T_Z+1$. For the DIAS $T=T_Z+2$. The IAS 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 DIAS (Fig. 3) is coherent superposition of elementary excitations like two protons–two neutron holes coupled to form the momentum $J=0^+$.

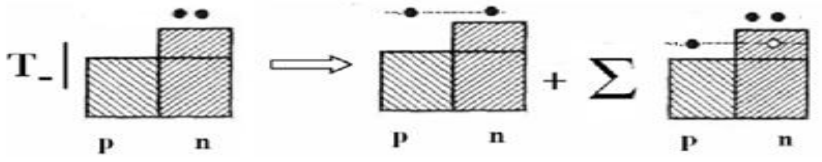

Figure 2. Structure of the IAS wave function when the parent state has the nn halo. The analog wave function involves two components corresponding to the pn and nn halo.

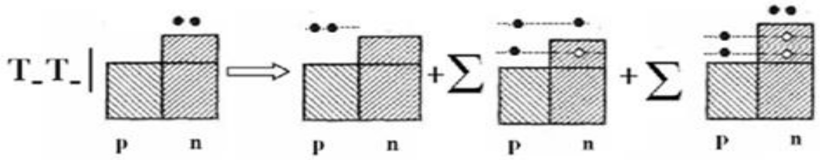

Figure 3. Structure of the DIAS wave function when the parent state has the nn halo. The double analog wave function involves three components corresponding to the pp, pn, and nn halo.

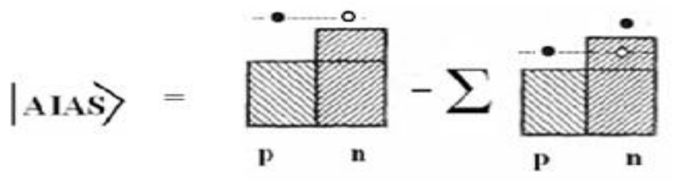

Figure 4. Structure of the AIAS wave function when the parent state has the n halo. The antianalog wave function involves two components corresponding to the p and n halo.

If the elementary excitations enter into the wave function incoherently, so-called configuration states (CS) are formed. In halolike nuclei formation of CS can be associated with core excitation, and in some case it can be forbidden by the Pauli principle. The isospin of the CS is smaller the analog isospoin by one, and the excitation energy of the CS is also lower than the analog excitation energy. One of the best studied CS is (Fig. 4) the antianalog state (AIAS). Since transformation of the neutron to the proton during the formation of IAS, DIAS, and CS is not followed by a change in the spatial and spin characteristics, the above excited states in the halolike nuclei will also have a halolike structure.

3. Halo Structure for the IAS, DIAS, and CS

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 $\boldsymbol{T}_{-}$ on the ground state wave function for the ^{6}He nucleus (T=1, T_z=1) results in the formation of the analogue state with the configuration corresponding to the pn halo. This analogue 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 Γ=8.2 eV, which corresponds to the half-life $T_{1/2}=6\cdot10^{-17}$ 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 $\boldsymbol{T}_{-}$ on the ground state wave function for the ^{6}He nucleus results in the formation of the double analogue 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 Γ=92keV, which corresponds to $T_{1/2}=5\cdot10^{-21}$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 [6,7]. The action of the operator $\boldsymbol{T}_{-}$ on the ^{11}Li ground state (T=5/2, T_z=5/2) results in the formation of the analogue 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 $\boldsymbol{T}_{-}$ on the ^{11}Li ground state (T=5/2, T_z=5/2) gives us the double analogue 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 analogue state will have three components corresponding to the nn, pn, and pp halo (Fig. 3).

Here formation of configurations states is not prohibited either under single or double action of the operator $\boldsymbol{T}_-$ on the ^{11}Li ground state. The configuration states will have lower excitation energy than the analogue resonance arising from the single action of the operator $\boldsymbol{T}_-$ and the double analogue resonance arising from the double action of the operator $\boldsymbol{T}_-$. The structure of the configuration states will correspond to the pn and nn halo at the single action of the operator $\boldsymbol{T}_-$. At the double action of the operator $\boldsymbol{T}_-$ 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 analogue and double analogue 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 $\boldsymbol{T}_-$ on the ^{11}Be ground state (T=3/2, T_z=3/2) results in the formation of the analogue resonance in the ^{11}B nucleus (T=3/2, T_z=1/2) with the excitation energy E_{IAS}=12.56 MeV. The wave function of this analogue 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 (antianalogue state, Fig.4) E_{AIAS} in ^{11}B (T=1/2, T_z=1/2) can be evaluated using [3] the relation

$$E_{IAS} - E_{AIAS} \approx -(2T+1)\cdot\frac{V}{A}, \; V \approx 100MeV, \qquad (1)$$

The antianalogue state is in the ^{11}B nucleus at the excitation energy of about 3.5MeV and has the structure of both the n halo and the p halo. On the repeated action of the operator $\boldsymbol{T}_-$ on the ^{11}Be ground state we obtain the double analogue 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 analogue resonance in ^{11}C has components corresponding to the n halo and p halo.

4. Conclusions

1.Such excited states and resonances as isobar analog, double isobar analog, and configuration states in halo nuclei can also have a halolike 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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