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Structure of β-decay strength function S_β(E) and Wigner spin-isospin SU(4) symmetry

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It is shown that when the parent nucleus has *nn* Borromean halo structure, then after Gamow-Teller (GT) β-decay of parent state or after M1 γ-decay of Isobar Analogue Resonance (IAR) the states with *np* tango halo structure or mixed *np* tango + *nn* Borromean halo structure can be populated. Resonances in the GT β-decay strength function S_β (E) of halo nuclei may have *np* tango halo structure or mixed np tango + *nn* Borromean halo structure. Demonstrated that the nuclei with Z/N ≈ 0.6 may correspond to the SU(4) region.

Keywords: borromean halo, tango halo, mixed halo, beta decay strength function, SU(4) symmetry, SU(4) region.

Introduction

The strength function $S_\beta(E)$ governs [1, 2] the nuclear energy distribution of elementary charge-exchange excitations and their combinations like proton particle (πp)-neutron hole (νh) coupled into a spin-parity I^π : $[\pi p \otimes \nu h]I^\pi$ and neutron particle (νp)-proton hole (πh) coupled into a spin-parity I^π : $[\nu p \otimes \pi h)]I^\pi$. The strength function of Fermi-type β-transitions takes into account excitations $[\pi p \otimes \nu h]0^+$ or $[\nu p \otimes \pi h]0^+$. Since isospin is a quite good quantum number, the strength of the Fermi-type transitions is concentrated in the region of the isobar-analogue resonance (IAR). The strength function for β-transitions of the Gamow-Teller (GT) type describes excitations $[\pi p \otimes \nu h]1^+$ or $[\nu p \otimes \pi h]1^+$. Residual interaction can cause collectivization of these configurations and occurrence of resonances in $S_\beta(E)$ [1, 2].

Generally the term "halo" is used when halo nucleon(s) spend(s) at least 50% of the time outside the range of the core potential, i.e. in the classically forbidden region [3, 5]. The necessary conditions for the halo formation are: the small binding energy of the valence particle(s), small relative angular momentum $L = 0,1$ for two-body or hyper momentum $K = 0,1$ for three-body halo systems, and not so high level density (small mixing with non-halo states). Coulomb barrier may suppresses proton-halo formation for $Z > 10$. Neutron and proton halos have been observed in several nuclei [3, 5]. In Borromean systems the two-body correlations are too weak to bind any pair of particles while the three-body correlations are responsible for the system binding as a whole. In states with one and only one bound subsystem the bound particles moved in phase and were therefor named "tango states" [4, 5].

When the nuclear parent state has the two-neutron (*nn*) Borromean halo structure, then IAR and configuration states (CSs) can simultaneously have *nn*, *np* Borromean halo components in their wave functions [6, 9]. After $M1$ γ-decay of IAR with np Borromean halo structure or GT β-decay of parent nuclei with *nn* Borromean halo structure, the states with *np* halo structure of tango type may be populated [7]. It is shown that the nuclei with $Z/N \approx 0.6$ may form the region with the Wigner spin-isospin SU(4) symmetry.

Beta decay strength function in halo nuclei

For the GT β-transitions essential configurations include states made up of the ground state of parent nucleus by the action of the Gamow-Teller operator of the β-transition [1, 2] Y_-:

$$Y_- = \sum \tau(i) - \sigma(i), \tag{1}$$

where τ (i) − σ (i) is a spin-isospin operator. Acting on ground state (g.s.) of parent nuclei by the operator Y - results in formation of configurations of proton particle (πp)-neutron hole (νh) coupled into a spin-parity $I^\pi = 1^+$. These are [1, 2] so called (Figure 1 - Figure 3) core polarization (CP), back spin flip (BSF), and spin flip (SF) configurations. Coherent superposition [1, 2] of CP, BSF, and SF configurations forms Gamow-Teller (GT) resonance. Non coherent superposition forms resonances in $S_\beta(E)$ at excitation energy E lower than energy of GT resonance (so called pigmy resonances). Because after action of Y-operator on *nn* Borromean halo configuration with $I^\pi = 0^+$ the *np* tango halo configurations with $I^\pi = 1^+$ are formed (Figure 1 - Figure 3), the GT and pigmy resonances in $S_\beta(E)$ will have components corresponging to *np* tango halo. When neutron excess number is enough high, the SF, CP, and BSF configurations may simultaneously have both *nn* Borromean halo component and *np* tango halo component and form so called mixed halo (Figure 1 - Figure 3).

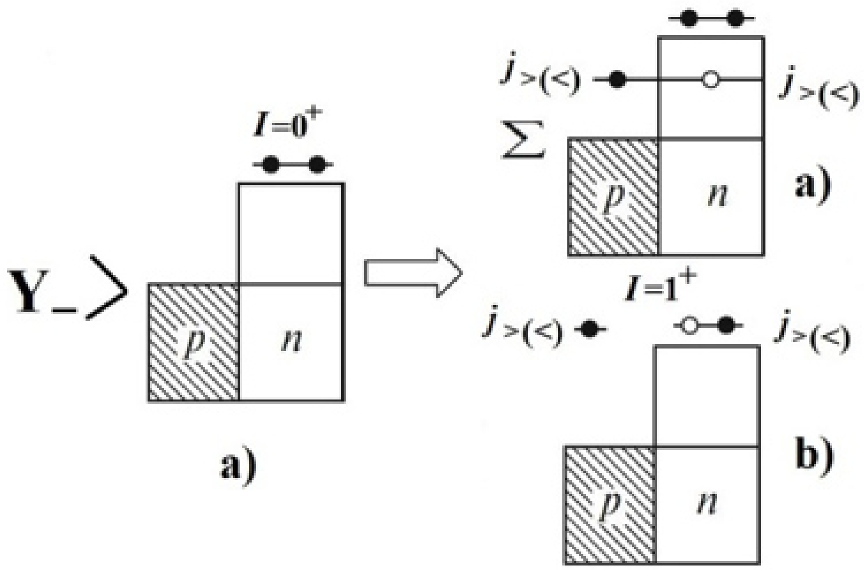

Figure 1. Proton particle–neutron hole coupled to form the spin-parity I = 1 $^+$ and core polarization (CP) states, where j> = l+1/2, j< = l–1/2, a) *nn* Borromean halo component, b) *np* tango halo component.

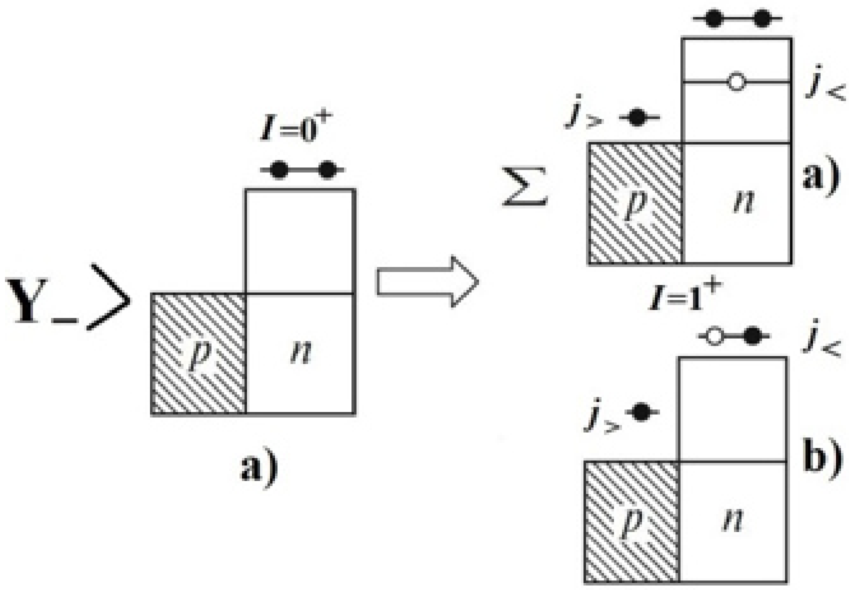

Figure 2. Proton particle–neutron hole coupled to form the spin-parity I = 1 $^+$ and back spin flip (BSF) states: a) *nn* Borromean halo component, b) *np* tango halo component.

Gamow-Teller β-decay of ^{6}He, M1 γ-decay of *IAR* in ^{6}Li and SU(4) region

Two neurons that form the *nn* halo in ^{6}He ground state (g.s.) occupy the $1p$ orbit ($p_{3/2}$ configuration with a 7% admixture of $p_{1/2}$ configuration). The remaining two neutrons and two protons occupy the 1s orbit. Therefore, the action of the operator T on the g.s. 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 *IAR* 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

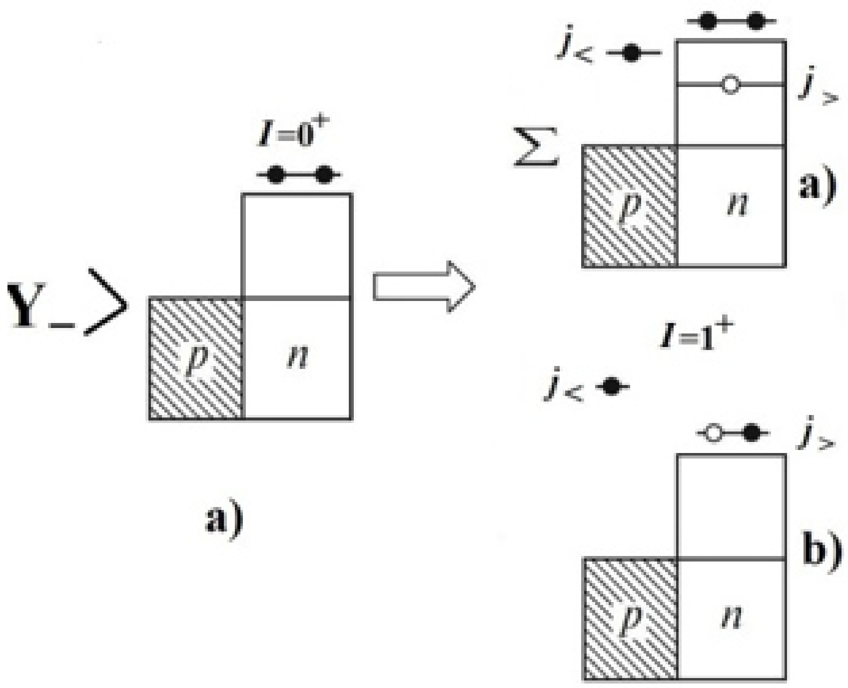

Figure 3. Proton particle–neutron hole coupled to form the spin-parity I = 1^+ and spin flip (SF) states: a) *nn* Borromean halo component, b) *np* tango halo component.

$T_{1/2} = 6 \cdot 10^{-17}$ s. The theoretical and experimental data [10-12] indicate that this *IAR* state has a *np* halo. Since the operators of GT β-decay and $M1$ γ-decay have no spatial components (the radial factor in the $M\lambda$ γ-transition operator is proportional to $r^{\lambda-1}$), GT β-transitions and $M1$ γ-transitions between states with similar spatial shapes are favored. The $M1$ γ-decay of IAS would be hindered [9] if the g.s. of ^{6}Li did not have a halo structure and would be enhanced if the g.s. of ^{6}Li has a halo structure. A rather large value of the reduced probability of $M1$ γ-transition ($B(M1,\sigma)$ = 8.2 W.u.) for $M1$ γ-decay from IAS and large B(GT) $\approx 5g_A{}^2/4\pi$ ($\sum$ (Ikeda sum rule) = $6g_A{}^2/4\pi$) value for β-transition to the ground state is evidence [9] for the existence of tango halo structure in the ^{6}Li ground state. Because of large B(GT) value (B(GT) $\approx 5g_A{}^2/4\pi$), the ^{6}Li g.s. has structure corresponding to the low-energy Gamow-Teller phonon [13, 14] and the energy of this GT phonon is lower than ($E_{GT} < E_{IAR}$) the energy of *IAR* (E_{IAR} = 3562.88 keV). In heavy and middle nuclei (Figure 4), because of repulsive character of the spin-isospin residual interaction [1, 15], the energy of Gamow-Teller resonance is larger than the energy of *IAR* ($E_{GT} > E_{IAR}$). The position of the Gamow-Teller resonance was calculated [1, 15] in the model with isospin-isospin and spin-isospin residual interaction. Model correctly describes the experimental data on the (p, n) reaction in which the Gamow-Teller resonance is exited in the final nucleus [1, 15]. This model was originally used to analyze $M1$ γ-decay of *IAR*, the β-decay strength functions from the spectra of delayed neutrons, and the probabilities of β-delayed fission.

It can be seen (Figure 4) that the position of the Gamow-Teller resonance depends on the shell structure and is described by a straight line only on the average.

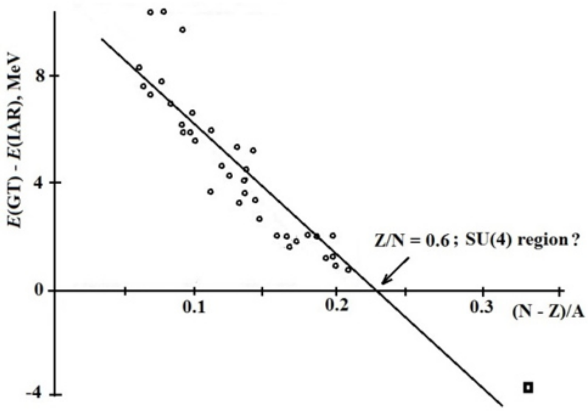

Figure 4. Difference of the $E_{GT} - E_{IAR}$ energies (circles) as a function of the neutron excess [15]. Datum for ^{6}He β–decay was added (square).

One of the consequence of the Wigner [16] spin-isospin SU(4) symmetry is $E_{GT} = E_{IAR}$. SU(4) symmetry-restoration effect [1, 15, 17] induced by the residual interaction, which displaces the GT towards the IAR with increasing (N-Z)/A. In tango halo nucleus ^{6}Li (g.s.) for low energy GT phonon we have $E_{GT} < E_{IAR}$, $E_{GT} - E_{IAR}$ = -3562.88 keV, and $(N-Z)/A = 0.33$ for ^{6}He (^{6}He g.s. is the parent state). Such situation may be connected with contribution of the attractive [13, 14] component of residual interaction in this nucleus. It will be very interesting to find a region of atomic nuclei, where the $E_{GT} \approx E_{IAR}$ and spin-isospin SU(4) symmetry determine the nuclear properties (SU(4) region). As it follows from estimation (Figure 4), value $Z/N \approx 0.6$ corresponds to the SU(4) region. It should be pointed out that $Z/N \approx 0.6$ is necessary, but not sufficient condition for SU(4) region, just as Franzini-Radicati mass relationship [18]. Relation $Z/N \approx 0.6$ indicates the region where different [19] SU(4) effects manifestation may be studied.

Conclusion

Gamow-Teller resonance and pygmy resonances in GT beta decay strength function S_{β}(E) for halo nuclei may have structure corresponging to np tango halo. When neutron excess is high enough, resonances in S_{β}(E) may simultaneously have both nn Borromean halo component and np tango halo component and form so-called mixed halo. Structure of resonances in S_{β}(E) is manifested in charge exchange reactions. Halo structure of some pygmy resonances is important for beta-decay analysis in halo nuclei. Demonstrated that the nuclei with $Z/N \approx 0.6$ may belong to the SU(4) region.

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