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STRUCTURE OF β-DECAY STRENGTH FUNCTION $S_\beta(E)$ IN HALO NUCLEI

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Структура силовой функции бета-распада $S_\beta(E)$ галоидальных ядер

Показано, что если материнское ядро имеет борромиевское $n{-}n$ гало, то после β^--распада типа Гамова–Теллера (GT) или после $M1$ гамма-распада соответствующего изобар-аналогового резонанса (IAR) могут заселяться состояния, имеющие структуру типа $n{-}p$ танго-гало или смешанного типа: $n{-}p$ танго-гало $+\,n{-}n$ борромиевское гало. Резонансы в силовой функции $S_\beta(E)$ GT β-распада также могут иметь структуру типа $n{-}p$ танго-гало или смешанного типа: $n{-}p$ танго-гало $+\,n{-}n$ борромиевское гало. Корректный учет структуры гало-компонент важен при анализе бета-распада гало-ядер, при анализе $M1$ гамма-распада IAR в гало-ядрах и анализе зарядовообменных реакций.

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Structure of β-Decay Strength Function $S_\beta(E)$ in Halo Nuclei

It is shown that when the parent nucleus has $n{-}n$ 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 $n{-}p$ tango halo structure or mixed $n{-}p$ tango $+\,n{-}n$ Borromean halo structure can be populated. Resonances in the GT β-decay strength function $S_\beta(E)$ of halo nuclei may have $n{-}p$ tango halo structure or mixed $n{-}p$ tango $+\,n{-}n$ Borromean halo structure. Correct interpretation of halo structure is important in experiments on β-decay study, treatment of $M1$ γ decay of IAR, and charge-exchange nuclear reactions analysis.

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

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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 momentum I^π: $[\pi p \otimes \nu h]^\pi_I$, and neutron particle (νp) – proton hole (πh), coupled into a momentum I^π : $[\nu p \otimes \pi h)]^\pi_I$. 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 quite a 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]. The position and intensity of resonances in $S_\beta(E)$ are calculated within various microscopic models of the nucleus [2]. At excitation energies E smaller than Q_β (total β-decay energy), $S_\beta(E)$ determines the features of the β decay. For higher excitation energies that cannot be reached with the β decay, $S_\beta(E)$ determines the charge-exchange nuclear reaction cross sections, which depend on the nuclear matrix elements of the β-decay type. From the macroscopic point of view, the resonances in the GT β-decay strength function $S_\beta(E)$ are connected with the oscillation of the spin–isospin density without change in the shape of the nucleus [1–3].

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 [4–6]. The necessary conditions for the halo formation are: small binding energy of the valence particle(s), small relative angular momentum $L = 0, 1$ for two-body or hypermomentum $K = 0, 1$ for three-body halo systems, and not so high level density (small mixing with non-halo states). Coulomb barrier may suppress proton-halo formation for $Z > 10$. Neutron and proton halos have been observed in several nuclei [4–6]. 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 therefore named "tango states" [5, 6].

When the nuclear parent state has a two-neutron ($n{-}n$) Borromean halo structure, then IAR and configuration states (CSs) can simultaneously have $n{-}n$, $n{-}p$ Borromean halo components in their wave functions [7–10]. After $M1$ γ decay of IAR with $n{-}p$ Borromean halo structure or GT β^- decay of parent nuclei with $n{-}n$ Borromean halo structure, the states with $n{-}p$ halo structure of tango type may be populated [8].

In this work, the structure of resonances in the GT β-decay strength function $S_\beta(E)$ for halo nuclei is discussed. It is shown that resonances in the GT β-decay strength function $S_\beta(E)$ of halo nuclei may have $n{-}p$ tango halo structure or mixed $n{-}p$ tango $+\,n{-}n$ Borromean halo components. Structure of $S_\beta(E)$ may be studied both in experiments on $M1$ γ decay of IAR and in experiments on $S_\beta(E)$ measurements in charge-exchange nuclear reactions and in β decay [1–3].

1. BETA-DECAY STRENGTH FUNCTION $S_\beta(E)$ IN HALO NUCLEI

The β-decay probability is proportional to the product of the lepton part described by the Fermi function $f(Q_\beta{-}E)$ and the nucleon part described by $S_\beta(E)$. For the Fermi β transitions, Gamow–Teller (GT) β transitions, FF β transitions in the ξ approximation (Coulomb approximation), and unique FF β transitions the reduced probabilities B(GT), $[B(\lambda\pi = 0^-) + B(\lambda\pi = 1^-)]$, and $[B(\lambda\pi = 2^-)]$, half-life $T_{1/2}$, level populations $I(E)$, strength function $S_\beta(E)$, and ft values are related as follows [2]:

$$d(I(E))/dE = S_\beta(E)\,T_{1/2}\,f(Q_\beta{-}E), \tag{1}$$

$$(T_{1/2})^{-1} = \int S_\beta(E)\,f(Q_\beta{-}E)\,dE, \tag{2}$$

$$\int\limits_{\Delta E} S_\beta(E)dE = \sum_{\Delta E} 1/(ft), \tag{3}$$

$$B(\mathrm{GT}, E) = [D(g_V^2/4\pi)]/ft, \tag{4}$$

$$B(\mathrm{GT}, E) = g_A^2/4\pi|\langle I_f||\sum t_\pm(k)\,\sigma_\mu(k)||I_i\rangle|^2/(2I_i+1), \tag{5}$$

$$[B(\lambda\pi = 2^-)] = 3/4[D\,g_V^2/4\pi]/ft, \tag{6}$$

$$[B(\lambda\pi = 0^-) + B(\lambda\pi = 1^-)] = [D\,g_V^2/4\pi]/ft, \tag{7}$$

where $D = (6147 \pm 7)$ s; Q_β is the total β-decay energy; $f(Q_\beta - E)$ is the Fermi function; t is the partial period of the β decay to the level with the excitation energy E; $1/ft$ is the reduced probability of β decay; $\langle I_f||\sum t_\pm(k)\,\sigma_\mu(k)||I_i\rangle$ is the reduced nuclear matrix element for the Gamow–Teller transition; I_i is the spin of the parent nucleus; I_f is the spin of the excited state of the daughter nucleus. By measuring populations of levels in the β decay, one can find the reduced probabilities and the strength function for the beta decay. The reduced probabilities of the beta decays are proportional to the squares of the nuclear matrix elements and reflect the fine structure of the strength function for the beta decay. For the Fermi β transitions essential configurations include the states made up of the ground state of daughter nucleus by the action of the nucleus isospin ladder operator T_{-}:

$$T_{-} = \sum a_i^{+}(p)\, a_i^{-}(n) = \sum \tau(i)_{-}. \tag{8}$$

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; that is, in (8) $a_i^{-}(n)$ is the operator for annihilation of the neutron in the state i, and $a_i^{+}(p)$ 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 beta-decay strength of the Fermi-type transitions is concentrated in the region of the isobar-analogue state (IAS).

The isobar-analogue state (IAS) is a collective state, which is a 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. 1). Let us take as a parent state the wave function for the ground state of the nucleus in which two neutrons make up the nuclear Borromean halo ($n{-}n$ halo) and act on it by the operator T_{-} (Fig. 1). As a result, we find that the wave function for the analogue state and configuration states involves components corresponding to the proton–neutron Borromean halo ($n{-}p$ halo) and two-neutron Borromean halo ($n{-}n$ halo) [7–10]. For some nuclei, configuration states are not formed by virtue of the Pauli principle, and the analogue wave function can lack the component corresponding to the $n{-}n$ halo.

For the GT β transitions, essential configurations include states made up of the ground state of daughter nucleus by the action of the Gamow–Teller operator

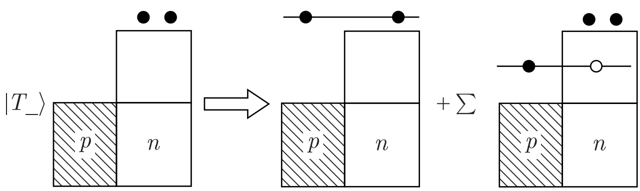

Fig. 1. Structure of the IAS wave function when the parent state has the Borromean $n{-}n$ halo. Proton particle – neutron hole coupled to form the momentum $I = 0^{+}$. The IAS wave function involves two components corresponding to the Borromean $p{-}n$ and Borromean $n{-}n$ halo

of the β transition [1, 2] Y_-:

$$Y_- = \sum \tau_-(i)\sigma_m(i), \quad (9)$$

where $\tau_-(i)\sigma_m(i)$ is a spin-isospin operator. Acting on g.s. of parent nuclei by the operator Y_- results in formation of proton particle (πp) – neutron hole (νh) coupled into momentum $I^\pi = 1^+$ configurations. These are [1, 2] the so-called (Fig. 2–4) core polarization (CP), back spin flip (BSF), and spin flip (SF) configurations.

Coherent superposition [1, 2] of CP, BSF, and SF configurations formed Gamow–Teller (GT) resonance (Fig. 5). Noncoherent superposition formed reso-

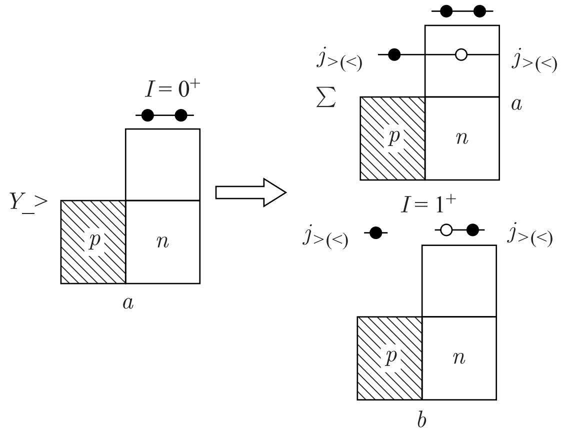

Fig. 2. Proton particle – neutron hole coupled to form the momentum $I = 1^+$ and core polarization (CP) states: *a*) $n{-}n$ Borromean halo component, *b*) $n{-}p$ tango halo component

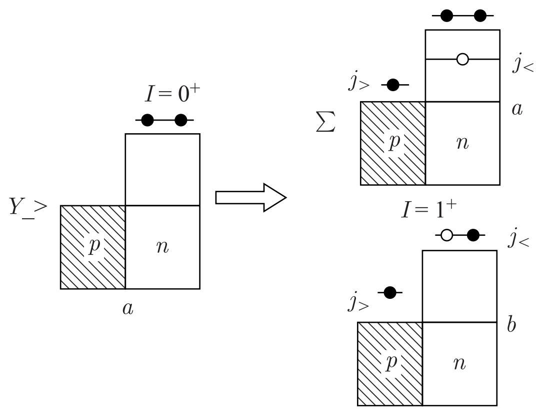

Fig. 3. Proton particle – neutron hole coupled to form the momentum $I = 1^+$ and back spin flip (BSF) states: *a*) $n{-}n$ Borromean halo component, *b*) $n{-}p$ tango halo component

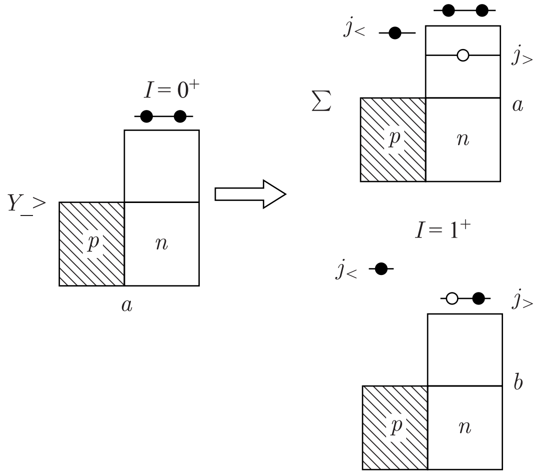

Fig. 4. Proton particle – neutron hole coupled to form the momentum $I = 1^+$ and spin flip (SF) states: *a*) $n-n$ Borromean halo component, *b*) $n-p$ tango halo component

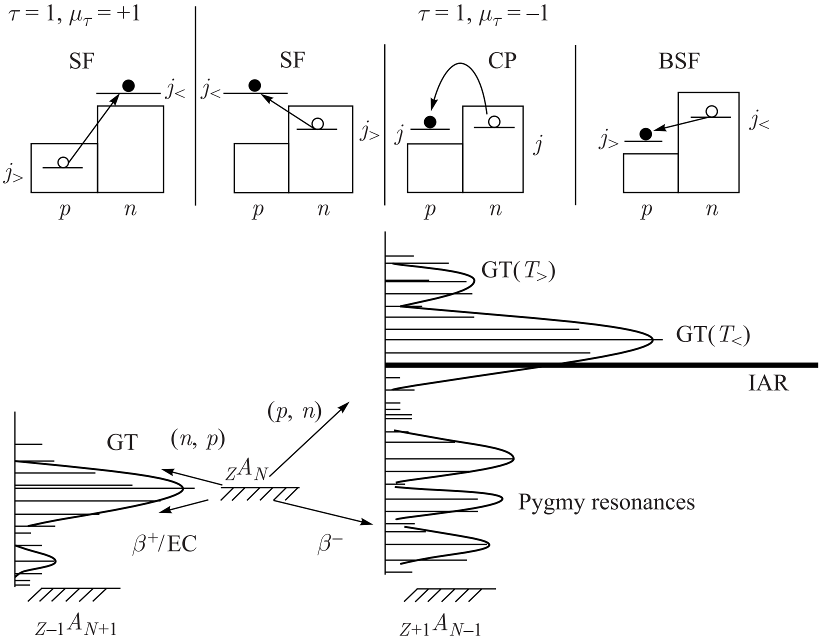

Fig. 5. Diagram [1, 2] of strength functions for GT β transitions and configurations that form resonances in $S_\beta(E)$ for GT transitions; τ — isospin of excitation, μ_τ — projection of isospin. The strength of the Fermi-type transitions is concentrated in the region of the isobar-analogue resonance

nances in $S_\beta(E)$ at GT excitation energy E lower than energy of GT resonance (the so-called pygmy resonances). Because after action of Y_- operator on $n-n$ Borromean halo configuration with $I^\pi = 0^+$ the $n-p$ tango halo configurations with $I^\pi = 1^+$ are formed (Figs. 2–4), the GT and pygmy resonances in $S_\beta(E)$ will have components corresponging to $n-p$ tango halo. When neutron excess number is high enough, the SF, CP, and BSF configurations may simultaneously have both $n-n$ Borromean halo component and $n-p$ tango halo component and form the so-called mixed halo (Figs. 2–4).

2. GAMOW–TELLER β^- DECAY OF ^{6}He AND $M1$ γ DECAY OF IAR IN ^{6}Li

Two neutrons that form the $n-n$ 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 $p-n$ halo. This IAS is in the ^{6}Li nucleus ($T = 1$, $T_z = 0$) at the excitation energy of 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 theoretical and experimental data [11–13] indicate that this IAS state has a $n-p$ halo. Formation of configuration states is prohibited by the Pauli principle. The isobar-analogue state (IAS) of the ^{6}He g.s. ($n-n$ Borromean halo nucleus), i.e., 3.56 MeV, $I = 0^+$ state of ^{6}Li, has [11, 12] a $n-p$ halo structure of Borromean type.

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 [10] if the g.s. of ^{6}Li did not have a halo structure and would be enhanced if the g.s. of ^{6}Li had a halo structure. The data on lifetime of IAS in ^{6}Li are given in [13], but the $M1$ γ decay branch is not determined. If one assumes that the total lifetime of IAS is determined by $M1$ γ decay, the reduced transition probability would be $B(M1) = 8.6$ W.u. Assuming the orbital part of the $M1$ γ-transition operator is neglected [14], $B(M1, \sigma)$ for $M1$ γ decay of IAS in ^{6}Li can be determined from the reduced probability ft of the ^{6}He β decay (Fig. 6). The $B(M1, \sigma)$ value proved to be 8.2 W.u., i.e., the probability of the $M1$ γ transition is close to the value for the upper limit [15] in the light nuclei region. 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 to the ground state is the evidence for the existence of tango halo structure in the ^{6}Li ground state. The IAS in ^{6}Li has the Borromean structure, since the $n-p$ subsystem is

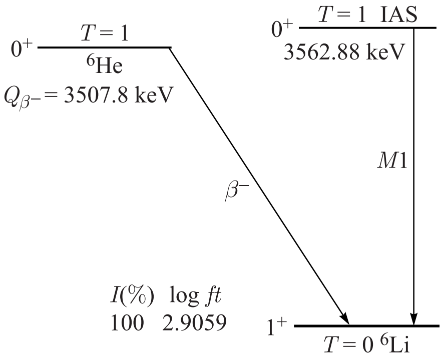

Fig. 6. Connection [14] between the ft value for β decay of the parent state (^{6}He g.s.) and the $B(M1,\sigma)$ value for γ decay of IAS (^{6}Li, $E = 3562$ keV). $ft = 11633/[T_0 \times B(M1,\sigma)]$, T_0-isospin of the parent state, ft in sec, $B(M1,\sigma)$ in μ_0^2, for $M1$ γ transition W.u. $= 1.79\mu_0^2$, $B(M1,\sigma) = 8.2$ W.u., $B(M1) \approx 8.6$ W.u.

coupled to the momentum $I = 0^+$, i.e., unbound, whereas $n{-}p$ subsystem for the ^{6}Li g.s. is coupled to the momentum $I = 1^+$, i.e., bound. According to halo classification [4, 5], such structure of the ^{6}Li g.s. corresponds to the $n{-}p$ tango halo.

CONCLUSIONS

Gamow–Teller resonance and pygmy resonances in GT beta-decay strength function $S_\beta(E)$ for halo nuclei may have structure corresponding to $n{-}p$ tango halo. When neutron excess is high enough, resonances in $S_\beta(E)$ may simultaneously have both $n{-}n$ Borromean halo component and $n{-}p$ tango halo component and formed the so-called mixed halo. Structure of resonances in $S_\beta(E)$ manifested in charge-exchange reactions. Halo structure of some pygmy resonances is important for beta-decay analysis in halo nuclei.

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