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I. N. Izosimov *

STRUCTURE OF β-DECAY STRENGTH FUNCTION $S_\beta(E)$ IN HALO NUCLEI, SPIN–ISOSPIN $SU(4)$ SYMMETRY, AND $SU(4)$ REGION

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* E-mail: izosimov@jinr.ru

Изосимов И. Н. Е6-2018-64

Структура силовой функции бета-распада $S_\beta(E)$ в галоидальных ядрах, спин-изоспиновая $SU(4)$-симметрия и область ядер с $SU(4)$-симметрией

В тяжелых и средних ядрах энергия $E_{\text{ГТР}}$ резонанса Гамова–Теллера (ГТР) превышает энергию $E_{\text{ИАР}}$ изобар аналогового резонанса (ИАР), $E_{\text{ГТР}} > E_{\text{ИАР}}$. В ядрах ^{6}Li и ^{11}Be для энергий супер-ГТ фононов (или ГТР) справедливо обратное соотношение $E_{\text{ГТР}} < E_{\text{ИАР}}$. Одним из следствий спин-изоспиновой $SU(4)$-симметрии Вигнера является равенство $E_{\text{ГТР}} = E_{\text{ИАР}}$. С помощью данных о величинах $E_{\text{ГТР}} - E_{\text{ИАР}}$ в работе показано, что ядра с $Z/N = 0{,}5{-}0{,}6$ могут соответствовать области $SU(4)$-симметрии, где $E_{\text{ГТР}} \approx E_{\text{ИАР}}$.

Проведен анализ резонансной структуры $S_\beta(E)$ для ГТ β^--распадов галоидальных ядер ^{6}He и ^{11}Li. Из сравнения экспериментальных значений полной силы β-переходов с правилом сумм Икеды получены значения отношений квадратов аксиально-векторной и векторной констант слабого взаимодействия: $(g_A^{\text{eff}}/g_V)^2 = 1{,}272 \pm 0{,}010$ для ^{6}He и $(g_A^{\text{eff}}/g_V)^2 = 1{,}5 \pm 0{,}2$ для ^{11}Li. Обсуждается изменение константы g_A^{eff} в галоидальных ядрах.

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Izosimov I. N. E6-2018-64

Structure of β-Decay Strength Function $S_\beta(E)$ in Halo Nuclei, Spin–Isospin $SU(4)$ Symmetry, and $SU(4)$ Region

In heavy and middle nuclei, the energy E_{GTR} of Gamow–Teller (GT) resonance (GTR) is larger than the energy E_{IAR} of isobar-analogue resonance (IAR), $E_{\text{GTR}} > E_{\text{IAR}}$. In ^{6}Li and ^{11}Be nuclei for low-energy super-GT phonons (or GTR), we have $E_{\text{GTR}} < E_{\text{IAR}}$. One of the consequences of Wigner's spin–isospin $SU(4)$ symmetry is $E_{\text{GTR}} = E_{\text{IAR}}$. Using these data we estimated that the value $Z/N = 0.5{-}0.6$ corresponds to the $SU(4)$ region, where $E_{\text{GTR}} \approx E_{\text{IAR}}$.

Resonance structure of the $S_\beta(E)$ for GT β^- decay of halo nuclei ^{6}He and ^{11}Li is analyzed. Comparing experimental total strength for β-transitions in $g_V^2/4\pi$ units with the Ikeda sum rule (in $(g_A^{\text{eff}})^2/4\pi$ units), one can determine the squared ratio of axial-vector and vector weak interaction constants value $(g_A^{\text{eff}}/g_V)^2$. We obtained $(g_A^{\text{eff}}/g_V)^2 = 1.272 \pm 0.010$ for ^{6}He and $(g_A^{\text{eff}}/g_V)^2 = 1.5 \pm 0.2$ for ^{11}Li β^- decays. Quenching of the weak axial-vector constant g_A^{eff} in halo nuclei is discussed.

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 [1–3] 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: $[\pi p \otimes \nu h]^\pi_I$ and neutron particle (νp) – proton hole (πh) coupled into a spin-parity 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 $S_\beta(E)$. In heavy and middle nuclei, because of repulsive character of the spin–isospin residual interaction [1, 2], the energy of GT resonance (GTR) is larger than the energy of IAR ($E_{\rm GTR} > E_{\rm IAR}$). One of the consequences of Wigner's spin–isospin $SU(4)$ symmetry is $E_{\rm GTR} = E_{\rm IAR}$. $SU(4)$ symmetry-restoration effect is induced by the residual interaction, which displaces GTR towards IAR with increasing $(N-Z)/A$.

In ^{6}Li nucleus (g.s. is the tango halo state [4–7], IAR is the Borromean halo resonance) for low-energy super-GT phonon (experimental reduced GT strength $B(\mathrm{GT}) = 7.630\, g_V^2/4\pi$, Σ (Ikeda sum rule) $= 6\, g_A^2/4\pi$) we have $E_{\rm GTR} < E_{\rm IAR}$, $E_{\rm GTR} - E_{\rm IAR} = -3562.88$ keV, and $(N-Z)/A = 0.33$ for ^{6}He (^{6}He g.s. is the parent Borromean halo state). In ^{11}Be nucleus ($E_{\rm IAR} = 21.16$ MeV corresponds to the Borromean halo IAR) for low-energy ($E = 18.19$ MeV) super-GT phonon or GTR (experimental reduced GT strength $B(\mathrm{GT}) = 23\, g_V^2/4\pi$, Σ (Ikeda sum rule) $= 15\, g_A^2/4\pi$) we have $E_{\rm GTR} < E_{\rm IAR}$, $E_{\rm GTR} - E_{\rm IAR} = -2.97$ MeV, and $(N-Z)/A = 0.45$ for ^{11}Li (^{11}Li g.s. is the parent Borromean halo state). Such a situation may be connected with contribution of the attractive [8, 9] component of residual interaction in these nuclei. It will be very interesting to find a region of atomic nuclei where the $E_{\rm GTR} \approx E_{\rm IAR}$ and spin–isospin $SU(4)$ symmetry determine the nuclear properties ($SU(4)$ region). From our estimations it follows that the value $Z/N = 0.5-0.6$ may correspond [7] to the $SU(4)$ region.

The free-nucleon value of axial-vector weak constant was measured in neutron beta decay and $g_A/g_V = -1.2723(23)$, $(g_A/g_V)^2 = 1.618 \pm 0.006$. Inside nuclear matter the value of g_A is effected by many nucleon correlations [10] and quenched or enhanced value of $g_A^{\rm eff}$ might be needed to reproduce experimental data. Comparing experimental total strength [1, 2, 11] for β decay in $g_V^2/4\pi$ units with the Ikeda sum rule (in $(g_A^{\rm eff})^2/4\pi$ units), one can determine the $(g_A^{\rm eff}/g_V)^2$ value. For ^{6}He we obtain $(g_A^{\rm eff}/g_V)^2 = 1.272 \pm 0.010$ and $(g_A^{\rm eff}/g_V)^2 = 1.5 \pm 0.2$ for ^{11}Li. Quenching of the weak axial-vector constant $g_A^{\rm eff}$ in halo nuclei is discussed.

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 $B(\mathrm{GT})$, $[B(\lambda\pi = 0^-) + B(\lambda\pi = 1^-)]$, 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 [1, 2, 7, 11]:

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

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

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

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

$$B^{\pm}(\mathrm{GT}, E) = [D(g_V^2/4\pi)]/ft, \tag{5}$$

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

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

where $D = (6144 \pm 2)$ 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. The position and intensity of resonances in $S_\beta(E)$ are calculated within various microscopic models of the nucleus [1, 2]. At excitation energies E smaller than Q_β (total β-decay energy), $S_\beta(E)$ determines the characters 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].

The conserved vector-current hypothesis (CVC) and partially conserved axial-vector-current hypothesis (PCAC) yield the free-nucleon [10] value $g_A/g_V = -1.27$. Inside nuclear matter the effective value g_A^{eff} is needed to reproduce experimental observations. Precise information on the value of g_A^{eff} is crucial when predicting half-life for beta decays, beta-decay strength function for Gamow–Teller (GT) and first forbidden (FF) beta transitions, and cross section for charge-exchange reactions. The effective value of g_A^{eff} is characterized by a renormalization factor q (in the case of quenching of g_A it is called "quenching factor"): $q = g_A^{\text{eff}}/g_A^{\text{free}}$, where $g_A^{\text{free}} = -1.2723(23)$ is the free-nucleon value of the axial-vector coupling measured in neutron beta decay, and g_A^{eff} is the value of the axial-vector coupling derived from a given theoretical or experimental analysis.

The renormalization of g_A, which stems from the nuclear-model effects, depends [10] on the nuclear-theory framework chosen to describe the nuclear many-body wave functions involved in the weak processes. This is why the effective values of g_A^{eff} can vary from one nuclear model to the other. The origin of the quenching of the g_A value is not completely known and various mechanisms have been proposed for its origin including tensor effects, the Δ-isobar admixture to the nuclear wave function, relativistic corrections to the Gamow–Teller operator, etc., but a clear separation of these aspects is difficult [10].

Also, the experimental methods of quenching value determination in many cases may have essential uncertainties [1, 2, 9]. One of the model-independent methods for g_A^{eff} determination [1] is the comparison of the experimental total GT beta-decay strength with the Ikeda sum rule. For application of this method it is necessary to have the total GT strength in the energy window allowed for beta decay. Such a situation may be realized [7] for beta decay of halo nuclei (^{6}He, ^{11}Li) or for very neutron-rich nuclei, where $E_{\text{GTR}} < E_{\text{IAR}}$. It is well known that the GT total strength satisfies the Ikeda sum rule, which is written as

$$S^- - S^+ = 3(N-Z), \tag{8}$$

$$S^\pm = \Sigma_f \left|\langle I_f \right|\left| \sum t_\pm(k)\,\sigma_\mu(k) \right|\left| I_i \rangle\right|^2 / (2I_i + 1), \tag{9}$$

$$\sum{}_j\, B^-(\text{GT}, E_j) - \sum{}_k\, B^+(\text{GT}, E_k) = 3(N-Z)(g_A^{\text{eff}})^2/4\pi, \tag{10}$$

where $B^-(\mathrm{GT}, E_j)$ and $B^+(\mathrm{GT}, E_k)$ are determined from (4) for charge-exchange processes of GT type and from (5) for GT β^- or β^+/EC decay. For correct application of the Ikeda sum rule, the total strengths S^- for the GT β^- decay and S^+ for the GT β^+/EC decay must be in the energy windows allowed for β^- and for β^+/EC decay, and contribution from non-nucleonic degrees of freedom (Δ isobar, for example) must be neglectable. When $S^+ \approx 0$ or $S^+ \ll S^-$, then for β^- decay one obtains

$$\sum{}_j D/ft_j = 3(N{-}Z)(g_A^{\mathrm{eff}}/g_V)^2, \tag{11}$$

and from β^--decay data one can estimate for mother nucleus the ratio $(g_A^{\mathrm{eff}}/g_V)^2$ or the quenching factor $q_{\mathrm{GT}} = g_A^{\mathrm{eff}}/g_A^{\mathrm{free}}$. Such a situation may be realized in halo nuclei [7], where $E_{\mathrm{GTR}} < E_{\mathrm{IAR}}$ and GTR (or low-energy super Gamow–Teller phonon [8, 9]) may be observed. The total strength of the GT β^- transitions for ^{6}He and ^{11}Li β^- decay can be measured and such a method can be applied for the g_A^{eff} value determination.

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 [12–14]. 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 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 suppress proton-halo formation for $Z > 10$. Neutron and proton halos have been observed in several nuclei [12–14]. 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" [13, 14].

When the nuclear parent state has the two-neutron ($n{-}n$) Borromean halo structure, then IAR [15] and configuration states (CSs) [4–6] can simultaneously have $n{-}n$, $n{-}p$ Borromean halo components in their wave functions. 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 [6].

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 [7].

For the Fermi β transitions, essential configurations include states made up of the ground state of daughter nucleus by the action of the nucleus isospin ladder operator T_- :

$$T_- = \sum a_i^+(p)\, a_i^-(n) = \sum \tau(i)_- \,. \tag{12}$$

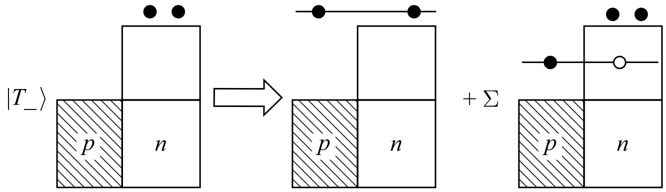

Fig. 1. Structure of the IAS wave function when the parent state has the Borromean $n{-}n$ halo. Proton particle – neutron hole coupled to form the spin-parity $I = 0^+$. The IAS wave function involves two components corresponding to the Borromean $p{-}n$ and Borromean $n{-}n$ halo

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 (12) $a_i^-(n)$ 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 analogue state (IAS) is a collective state, which is a coherent superposition of elementary excitations like proton particle – neutron hole coupled to form the spin-parity $I = 0^+$, i.e., all elementary excitations enter into the wave function of the analogue with one sign (Fig. 1). 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 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) [4–6, 15]. 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 (g.s.) of daughter nucleus by the action of the Gamow–Teller operator of the β transition [7] Y_- :

$$Y_- = \sum \tau_-(i)\sigma_m(i), \tag{13}$$

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 a spin-parity $I^\pi = 1^+$ configurations. These are [1, 2] the so-called (Figs. 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 resonances in $S_\beta(E)$ at GT excitation energy E lower than energy of GT resonance (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 corresponding to $n{-}p$ tango halo. When neutron excess number is high enough, the SF, CP, and BSF configurations may simultaneously have $n{-}n$ Borromean halo component and $n{-}p$ tango halo component and form the so-called mixed halo (Figs. 2–4).

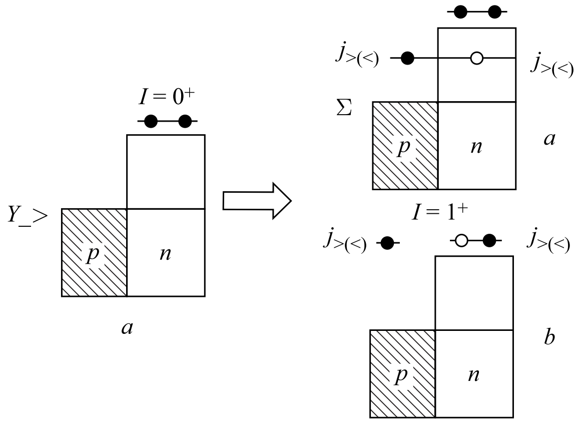

Fig. 2. Proton particle – neutron hole coupled to form the spin-parity $I = 1^+$ and core polarization (CP) states: *a*) $n{-}n$ Borromean halo component, *b*) $n{-}p$ tango halo component

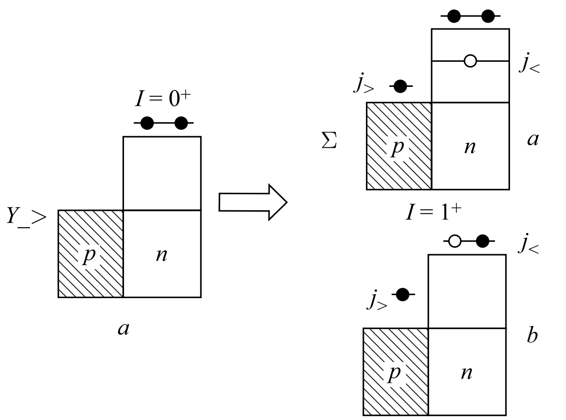

Fig. 3. Proton particle – neutron hole coupled to form the spin-parity $I = 1^+$ and back spin flip (BSF) states: *a*) $n{-}n$ Borromean halo component, *b*) $n{-}p$ tango halo component

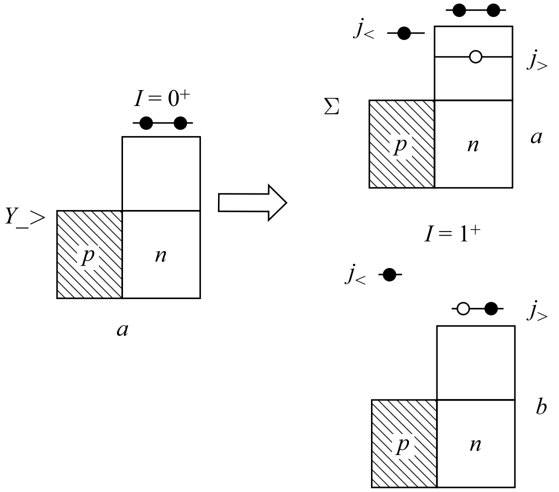

Fig. 4. Proton particle – neutron hole coupled to form the spin-parity $I = 1^+$ and spin flip (SF) states: *a*) $n{-}n$ Borromean halo component, *b*) $n{-}p$ tango halo component

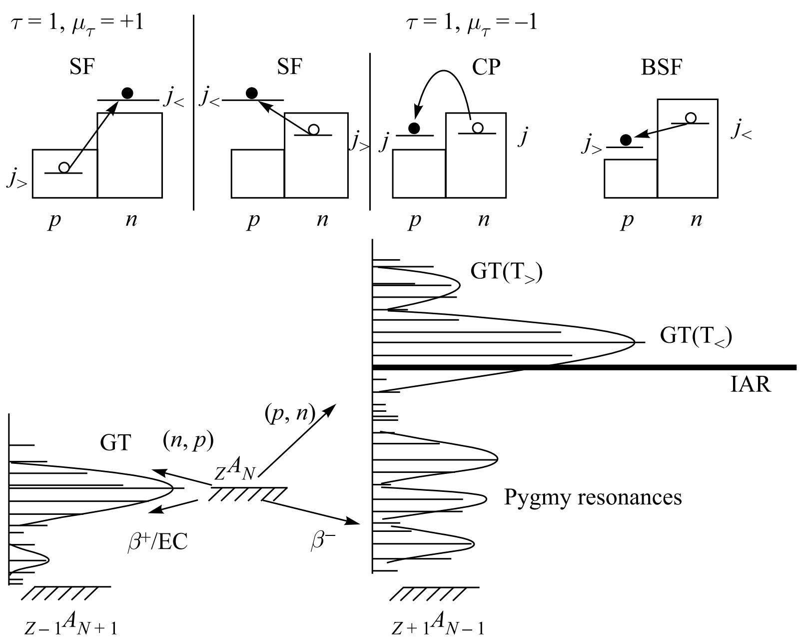

Fig. 5. Diagram [1, 2] of strength functions for GT β transitions and configurations that form resonances in $S_\beta(E)$ for GT transitions; τ — isospin of excitation, μ_τ — projection of isospin. The strength of the Fermi-type transitions is concentrated in the region of IAR

2. GAMOW–TELLER β^- DECAY OF ^{6}He

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 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 [15–16] 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 [15, 16] 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 favoured.

The $M1$ γ decay of IAS would be hindered [6] 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 [17], 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 [18], $B(M1, \sigma)$ for $M1$ γ decay of IAS in ^{6}Li can be determined from the reduced probability $1/ft$ 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 [19] in the light nuclei region. A rather large value of the reduced probability of

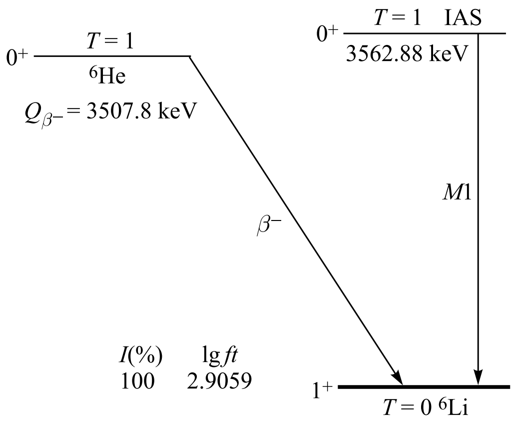

Fig. 6. Connection [14] between the ft value for β decay of the parent state (^{6}He g.s.) and the $B(M1,\ \sigma)$ value for γ decay of IAS (^{6}Li, $E = 3562$ keV). $ft = 11633/[T_0 \times B(M1, \sigma)]$, T_0 — isospin of the parent state, ft in sec, $t_{1/2} = (806.7 \pm 1.5)$ ms, $B(M1, \sigma)$ 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.

$M1$ γ transition ($B(M1, \sigma) = 8.2$ W.u.) for $M1$ γ decay from IAS and large $B(\mathrm{GT}) = 7.630\, g_V^2/4\pi$ value for β^- transition to the ground state is the evidence (Σ (Ikeda sum rule)$= 6\, g_A^2/4\pi$) for the existence of tango halo structure in the ^{6}Li ground state [5–7]. The IAS in ^{6}Li has the Borromean structure since the $n{-}p$ subsystem is coupled to the spin-parity $I^\pi = 0^+$, i.e., unbound, whereas $n{-}p$ subsystem for the ^{6}Li g.s. is coupled to the spin-parity $I^\pi = 1^+$, i.e., bound. According to halo classification [13, 14], such a structure of the ^{6}Li g.s. corresponds to the $n{-}p$ tango halo.

In heavy and middle nuclei not far from β-stability line, because of repulsive character of the spin–isospin residual interaction [1, 11], the energy of Gamow–Teller resonance is larger than the energy of IAR, i.e., $E_{\mathrm{GTR}} > E_{\mathrm{IAR}}$. For neutron-rich nuclei far from beta-stability line, the shell model [20] predicts that the GTR energy can be lower than the IAR energy, i.e., $E_{\mathrm{GTR}} - E_{\mathrm{IAR}} < 0$ for very neutron-rich nuclei.

From experimental value $t_{1/2} = (806.7 \pm 1.5)$ ms, lg $ft = 2.9059$ s [17, 21] and using (5) we determine (Fig. 7) that $B(\mathrm{GT}) = (7.63 \pm 0.07)\, g_V^2/4\pi$ for GT β^- decay of ^{6}He. Because of large $B(\mathrm{GT})$ value, the ^{6}Li g.s. has a structure corresponding to the low-energy super Gamow–Teller phonon [7–9], and the energy of this super-GT phonon (or GTR) is lower than the energy of IAR ($E_{\mathrm{IAR}} = 3562.88$ keV, $E_{\mathrm{GTR}} = 0$ keV). Such a situation may be connected with the contribution of the attractive [8, 9] component of residual interaction in this nucleus. Comparing the experimental (Fig. 7) value of $B(\mathrm{GT})$ with the Ikeda sum rule (10), (11), we obtained that $(g_A^{\mathrm{eff}}/g_V)^2 = 1.272 \pm 0.010$ for ^{6}He.

In the case that spin–isospin and isospin vertex properties in the nuclear medium appear to be close [22] as they should be in $SU(4)$ symmetry,

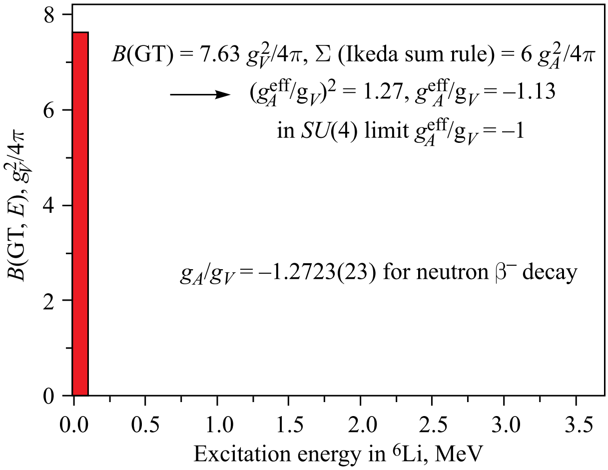

Fig. 7. Structure of the β-decay strength function for ^{6}He GT β^- decay in $g_V^2/4\pi$ units

$(g_A^{\rm eff}/g_V)^2 = 1$ should be in the $SU(4)$ limit. The experimental nuclear beta-transition quenching effect in ^{6}He $(g_A^{\rm eff}/g_V)^2 = 1.272 \pm 0.010$ may be regarded as a restoration of Wigner's spin–isospin $SU(4)$ symmetry of bare nucleons in nuclear medium after breaking $SU(4)$ symmetry in vacuum, where $(g_A^{\rm free}/g_V)^2 = 1.618 \pm 0.006$.

3. GAMOW–TELLER β^- DECAY OF ^{11}Li

Two neutrons that form the $n{-}n$ halo occupy the $2s$ and $1p$ orbits. The ^{11}Li ground state wave function has the form [14]:

$$\big|\big|\Psi(^{11}{\rm Li})\,\big\rangle \approx \big|\big|\Psi(^{9}{\rm Li}) \otimes 2n\,\big\rangle, \tag{14}$$
$$\big|\big|\Psi(^{9}{\rm Li}) \otimes 2n\,\big\rangle \approx a_s\big|\big|\Psi(^{9}{\rm Li}) \otimes (2s_{1/2})^2\,\big\rangle + a_p\big|\big|\Psi(^{9}{\rm Li}) \otimes (1p_{1/2})^2\,\big\rangle.$$

The ground state structure of ^{11}Li has been the subject of much discussion. Theoretical calculations showed that the admixture of approximately equal contributions of $(2s_{1/2})^2$ and $(1p_{1/2})^2$ components gave the best fit to the experimentally measured narrow momentum distribution of ^{9}Li after breakup of ^{11}Li.

^{11}Li g.s. $(J^\pi = 3/2^-)$ **β-decay scheme,** $(g_A^{\rm eff}/g_V)^2 = 1.5 \pm 0.2$**,** $E_{\rm GTR} = 18.19$ **MeV,** $E_{\rm IAR} = 21.16$ **MeV** $(I^\pi = 3/2^-,\ T = 5/2)$

Decay to ^{11}Be, $E_{\rm level}$, MeV [17, 23]	I^π [17, 23]	Branching ratio, % [17, 23]	lg ft [17, 23]	B(GT) in $(g_V)^2/4\pi$, (5) was used	B(GT) in $(g_A^{\rm eff})^2/4\pi$, (11) was used
0.32	$1/2^-$	7.7 ± 0.8	5.67 ± 0.04	0.013	0.0085
2.69	$3/2^-$	17 ± 4	5.06 ± 0.10	0.053	0.035
3.41	$(3/2^-)$	0.9 ± 0.4	6.25 ± 0.10	0.0035	0.0022
3.890 ± 0.001	$5/2^-$	22.7 ± 4.5	$4.78^{+0.07}_{-0.10}$	0.102	0.066
$3.969^{+0.02}_{-0.009}$	$3/2^-$	6.8 ± 2.4	$5.30^{+0.28}_{-0.13}$	0.0308	0.02
5.24	$5/2^-$	2.4 ± 0.5	5.55 ± 0.08	0.017	0.011
7.03	$(5/2^-)$	0.86 ± 0.17	5.77 ± 0.09	0.01	0.0068
8.02 ± 0.02	$3/2^-$	15.5 ± 3.1	4.30 ± 0.08	0.308	0.2
8.82	$3/2^-$	8.9 ± 1.4	4.46 ± 0.07	0.213	0.138
10.06	$5/2^-$	7.8 ± 1.8	4.18 ± 0.12	0.406	0.264
16.3		0.048 ± 0.007	4.66 ± 0.08	0.138	0.089
18.19		0.55 ± 0.06	2.45 ± 0.13	21.81	14.159
				$\Sigma = 23\,(g_V)^2/4\pi$	Ikeda sum rule $\Sigma = 15\,(g_A^{\rm eff})^2/4\pi$

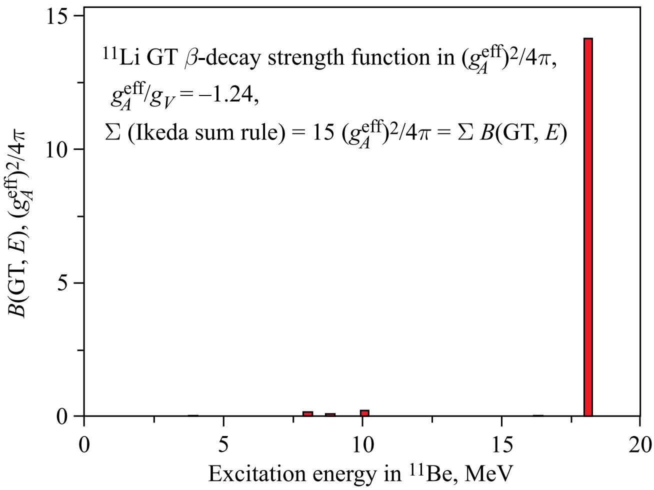

Fig. 8. Structure of the β-decay strength function for ^{11}Li GT β^- decay in $(g_A^{\rm eff})^2/4\pi$ units

The relative contributions of s- and p-components were determined in a one-neutron knockout experiment. The data were fitted using first spherical Hankel functions for the s- and p-neutrons, with the result that ^{11}Li ground state contains a $45 \pm 10\%$ $(2s_{1/2})^2$ component [14].

From experimental data on ^{11}Li β^- decay [17, 23], using (5) we obtained $B(\mathrm{GT}, E)$ values and constructed the β^--decay strength function for GT β^- transitions (table and Fig. 8).

Because GT strength B(GT) for resonance at 18.19 MeV energy has a large value ($B(\mathrm{GT}) = 21.8\,(g_V)^2/4\pi$, see the table), we conclude that this resonance ($E_{\mathrm{GTR}} = 18.19$ MeV) in ^{11}Be corresponds to GTR. For ^{11}Be we have [15, 17, 23] $E_{\mathrm{IAR}} = 21.16$ MeV, i.e., $E_{\mathrm{GTR}} < E_{\mathrm{IAR}}$.

Comparing the experimental value (table and Fig. 8) of total sum of B(GT) with the Ikeda sum rule (11), (12) we obtained that $(g_A^{\rm eff}/g_V)^2 = 1.5 \pm 0.2$ for ^{11}Li.

4. EVOLUTION OF $E_{\mathrm{GTR}} - E_{\mathrm{IAS}}$ TOWARDS NEUTRON-RICH NUCLEI AND $SU(4)$ REGION

In the case of precise Wigner's symmetry IAR and GTR energies are degenerate and we may expect that $E_{\mathrm{IAR}} \approx E_{\mathrm{GTR}}$. In the experimental and theoretical analysis of GTR data one noticed the tendency of GTR and IAR energies to converge with $(N-Z)/A$ increase [1, 11, 22]. This fact may be interpreted as an approximate $SU(4)$ symmetry realization in a definite nuclear area, namely, for nuclei with grate $(N-Z)/A$. $SU(4)$ symmetry-restoration effect [1, 11, 22, 24]

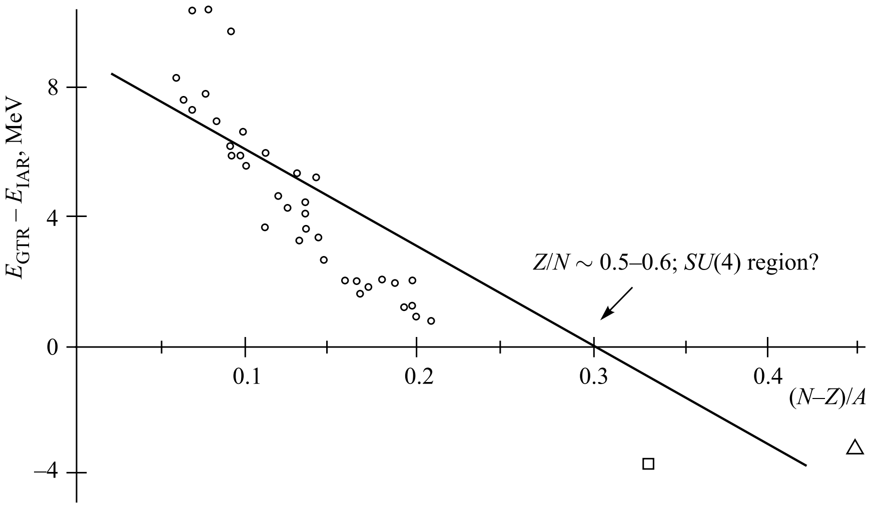

Fig. 9. The difference of the $E_{\rm GTR} - E_{\rm IAR}$ energies (circles) as a function of the neutron excess [1, 11]. Data for ^{6}He (square) and for ^{11}Li (triangle) β^- decays were added

is induced by the residual interaction, which displaces the GTR towards the IAR with increasing $(N{-}Z)/A$. It will be very interesting to find a region of atomic nuclei where the $E_{\rm GTR} \approx E_{\rm IAR}$ and spin–isospin $SU(4)$ symmetry determine the nuclear properties ($SU(4)$ region). From simple estimation (Fig. 9) it follows that the value $Z/N \approx 0.5{-}0.6$ corresponds to the $SU(4)$ region.

The interesting feature shown in Fig. 9 is that the GTR energy is lower than the IAR energy for very neutron-rich nuclei. There is more complicated dependence of $E_{\rm GTR} - E_{\rm IAR}$ on $(N{-}Z)/A$ than linear for the nuclei far from β-stability line. Shell model [20] also predicts that the GTR energy can be lower than the IAR energy, i.e., $E_{\rm GTR} - E_{\rm IAR} < 0$ for very neutron-rich nuclei. It is thus interesting to measure in more detail the evolution of $E_{\rm GTR} - E_{\rm IAR}$ for neutron-rich nuclei far from β-stability line.

CONCLUSIONS

The 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 form the so-called mixed halo. Structure of resonances in $S_\beta(E)$ manifested in charge-exchange reactions. Halo structure of GTR and pygmy resonances is important for beta-decay analysis in halo nuclei.

The quenching of g_A can be observed in GT β^- decay of halo nuclei, where $E_{\rm GTR} < E_{\rm IAR}$ and GTR (or low-energy super Gamow–Teller phonon [8, 9]) may be observed in halo nuclei [7]. Method of $g_A^{\rm eff}$ determination by comparison of experimental value S^- for GT β^- transitions with the Ikeda sum rule is the model-independent method and it may be applied for some halo nuclei.

Resonance structure of the $S_\beta(E)$ for β^- decay of halo nuclei ^{6}He and ^{11}Li is analyzed. Comparing experimental total strength for β decay in $g_V^2/4\pi$ units with the Ikeda sum rule (in $(g_A^{\rm eff})^2/4\pi$ units), we obtained $(g_A^{\rm eff}/g_V)^2 = 1.272 \pm 0.010$ for ^{6}He GT β^- decay and $(g_A^{\rm eff}/g_V)^2 = 1.5 \pm 0.2$ for ^{11}Li GT β^- decay.

Analysis of the evolution of $E_{\rm GTR} - E_{\rm IAS}$ towards very neutron-rich nuclei was done. It was shown that the value $Z/N = 0.5{-}0.6$ corresponds to the $SU(4)$ region.

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Издательский отдел Объединенного института ядерных исследований
141980, г. Дубна, Московская обл., ул. Жолио-Кюри, 6.
E-mail: publish@jinr.ru
www.jinr.ru/publish/