Structure of beta-decay strength function $S_\beta(E)$ and quenching of axial-vector weak interaction constant in halo nuclei

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Abstract. Resonance structure of the beta decay strength function $S_\beta(E)$ for GT β^--decay of halo nuclei ^{6}He and ^{11}Li is analyzed. Compare experimental total strength for β-transitions in $g_V^2/4\pi$ units with the Ikeda sum rule (in $(g_A^{eff})^2/4\pi$ units) one can determine the squared ratio of axial-vector and vector weak interaction constants value $(g_A^{eff}/g_V)^2$. We obtained $(g_A^{eff}/g_V)^2 = 1.272\pm0.010$ for ^{6}He and $(g_A^{eff}/g_V)^2 = 1.5\pm0.2$ for ^{11}Li β^--decays. Quenching of the weak axial-vector constant g_A^{eff} in halo nuclei is discussed. Analysis of the evolution of E_{GTR} - E_{IAS} toward neutron-rich nuclei was done. It is shown that the value $Z/N \approx 0.6$ corresponds to the SU(4) Wigner's spin-isospin symmetry region.

1 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 : $[\pi p\otimes\nu h]I^\pi$ 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 $[\nu p\otimes\pi h]0^+$. According to the isospin selection rule, the only state which can be reached by the Fermi beta transition is 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 $S_\beta(E)$.

Structure of the beta decay strength function and gamma decay in halo nuclei were analyzed in [4-7]. Using data on β-decay of ^{6}He, it was shown that the value $Z/N = 0.6$ may correspond [7] to the Wigner's spin-isospin SU(4) symmetry region. 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 ($E_{GTR} > E_{IAR}$). One of the consequences of Wigner's spin-isospin SU(4) symmetry is $E_{GTR} = E_{IAR}$. In ^{6}Li nucleus [7-9] we have $E_{GTR} < E_{IAR}$. Such situation may be connected with contribution of the attractive [8,9] component of residual interaction in this nucleus.

In this work resonance structure of the beta decay strength function $S_\beta(E)$ for GT β^--decay of halo nuclei ^{6}He and ^{11}Li is analyzed and $(g_A^{eff}/g_V)^2$ values were determined. The free-nucleon value of axial-vector weak constant g_A^{free} was measured [10] in neutron beta decay and $(g_A^{free}/g_V)^2 = 1.618\pm0.006$. Inside nuclear matter the value of g_A is effected by many nucleon correlations [11] and quenched or enhanced value of g_A^{eff} might be needed to reproduce experimental data. Comparing experimental total strength [1,2,12] for β-decay in $g_V^2/4\pi$ units with Ikeda sum rule (in $(g_A^{eff})^2/4\pi$ units), one can estimate the $(g_A^{eff}/g_V)^2$ value.

For ^{6}He we obtained $(g_A^{eff}/g_V)^2 = 1.272\pm 0.010$ and $(g_A^{eff}/g_V)^2 = 1.5\pm 0.2$ for ^{11}Li. Quenching of the weak axial-vector constant g_A^{eff} in halo nuclei is discussed.

2 Beta-decay strength function $S_\beta(E)$

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 $S_\beta(E)$. Beta decay strength function reflects the distribution of the squared β-decay matrix elements with respect to the excitation energy of the nuclear states of the daughter nucleus. Level occupancy after the β-decay $I(E)$, the half-life $T_{1/2}$, and ft values are related to $S_\beta(E)$ by the equations [1,2]:

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

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

$$\int_{\Delta E} S_\beta(E) dE = \sum_{\Delta E} 1/(ft), \quad (3)$$

where $S_\beta(E)$ is in units Mev^{-1} s^{-1}, and ft is in seconds.
The reduced probabilities of the GT transitions B(GT,E) are related with ft, g_V, and g_A values as [1,2,7,12-14]:

$$B^{\pm}(\mathrm{GT},E)=((g^{eff}{}_A)^2/4\pi)\,|\langle I_f\|\sum t_{\pm}(k)\sigma(k)\|I_i\rangle|^2/(2I_i+1), \quad (4)$$

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

where I_i and I_f are the spins of the initial and final states; g_A and g_V are the constants of the axial-vector and vector components of the β-decay; $D = (6144 \pm 2)$ sec; Q_β is the

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total β-decay energy; $t_{\pm}(k)\sigma(k)$ is the product of the isospin and spin operators giving the respective operators of the Gamow–Teller β-transitions; t is the partial period of the β-decay to the level with the excitation energy E; $\langle I_f \| \sum t_{\pm}(k)\, \sigma(k) \| I_i \rangle$ is the reduced nuclear matrix element for the Gamow–Teller transition.

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, $S_\beta(E)$ 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 [10,11] value $g_A^{free}/g_V = -1.2723(23)$. 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 [11] 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”): $q=g_A^{eff}/g_A^{free}$, where g_A^{eff} is the value of the axial-vector coupling derived from a given theoretical or experimental analysis.

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, and contribution from non-nucleonic degries of freedom (Δ-isobar, for example) must be neglectable. Such situation may be realized [7] for beta decay of halo nuclei (^{6}He, ^{11}Li) or for very neutron-rich nuclei where, $E_{GTR} < E_{IAR}$.

It is well known that the GT total strength satisfies the Ikeda sum rule, which is written as:

$$S^- - S^+ = 3(N-Z), \quad (6)$$

$$S^{\pm} = \Sigma_f \left| \langle I_f \| \sum t_{\pm}(k)\, \sigma(k) \| I_i \rangle \right|^2 / (2I_i + 1), \quad (7)$$

$$\sum_j B^-(GT,E_j) - \sum_k B^+(GT,E_k) = 3(N-Z)(g^{eff}_A)^2/4\pi, \quad (8)$$

where $B^-(GT,E_j)$ and $B^+(GT,E_k)$ determined from (4) for charge-exchange processes of GT type and from (5) for GT β^- or β^+/EC decay. When $S^+ \approx 0$ or $S^+ \ll S^-$, than for β^- - decay one obtains:

$$\sum_j D/ft_j = 3(N-Z)\,(g^{eff}_A/g_V)^2\,, \quad (9)$$

and from β^--decay data one can estimate for mother nuclus the ratio $(g^{eff}_A/g_V)^2$ or the quenching factor q_{GT}.

3 Gamow-Teller β^--decay of ^{6}He

Structure and region of halo nuclei were described in many reviews [15-17]. IAS in ^{6}Li (Fig.1) has a halo structure [18,19]. Since the operators of GT β-decay and $M1$ γ-decay [20] have no spatial components, GT β-transitions and $M1$ γ-transitions between states with similar spatial shapes are favoured. The $M1$ γ-decay of IAS would be hindered [6,7] 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. Data [21] on β-decay of ^{6}He are presented in Fig.1. A rather large value of the reduced probability of $M1$ γ-transition for $M1$ γ-decay from IAS and large B(GT) value for β^--transition to the ground state is evidence for the existence of tango halo structure in the ^{6}Li g. s. [5-7].

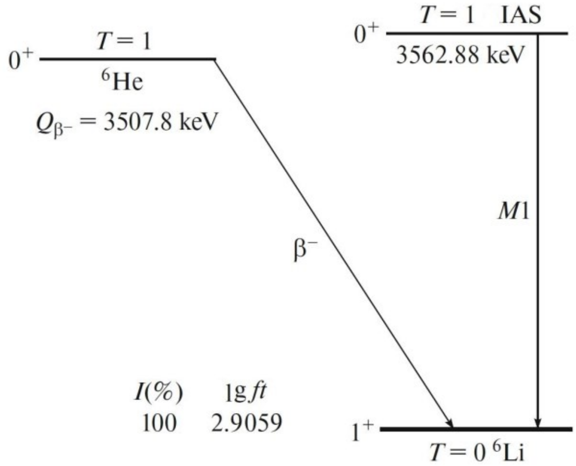

Fig. 1. ^{6}He β-decay and $M1$ γ-decay of corresponding IAS.

Only one additional resonance $I^\pi = 1^+$ with excitation energy 5.65 MeV was observed in ^{6}Li [10,22]. B(GT) value for this resonance does not measured. Theoretical estimation [23] gives small B(GT) for 5.65 MeV resonance and we neglected by its contribution to the Ikeda sum rule.

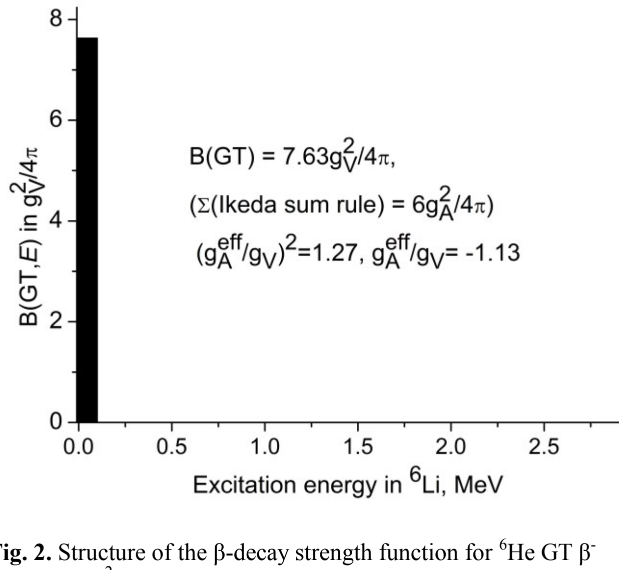

Fig. 2. Structure of the β-decay strength function for ^{6}He GT β^--decay in $g_V^2/4\pi$ units.

From experimental value [10,22] $t_{1/2} = 806.7 \pm 1.5$ ms, lgft = 2.9059 and using (5) we determine (Fig.2) that

B(GT) = $(7.63\pm0.07)g_V^2/4\pi$ for GT β^--decay of ^{6}He (Σ(Ikeda sum rule) = $6g_A^2/4\pi$). Compare the experimental value of B(GT) with the Ikeda sum rule (8), (9), we obtained that $(g_A^{eff}/g_V)^2 = 1.272\pm 0.010$ for ^{6}He.

In the case that spin-isospin and isospin vertex properties in the nuclear medium appear to be close [24] as they should be in SU(4) symmetry, and $(g_A^{eff}/g_V)^2 = 1$ should be in the SU(4) limit. The experimental nuclear beta transition quenching effect in ^{6}He $(g_A^{eff}/g_V)^2$ = 1.272 ± 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 $(g_A^{free}/g_V)^2 = 1.618\pm0.006$.

For $|$N-Z$|$ » 0 nuclei the maximum excitation energy corresponds to the main resonance in $S_\beta(E)$. Other, more weak resonances [1,2] (pygmy resonances) have smaller excitation energies. Such type of $S_\beta(E)$ take place for ^{11}Be (Fig.3).

For N≈Z nuclei structure of $S_\beta(E)$ may have opposite type, i.e. the minimum [8,9,23] excitation energy corresponds to the main resonance in $S_\beta(E)$. Such type of S_β(E) take place for ^{6}Li (Fig.2). For ^{6}Li we have (Fig.1, [7]) $E_{GTR} < E_{IAR}$, $E_{GTR} - E_{IAR} = -3562.88$ keV.

4 Gamow-Teller β^--decay of ^{11}Li

From experimental data on ^{11}Li β^--decay [10,25], using (5) we obtained B(GT,E) values and constructed the β^--decay strength function for GT β^--transitions (Table 1 and Fig. 3).

Table 1. ^{11}Li. (g.s I^π =3/2$^-$) β^- – decay , $(g_A^{eff}/g_V)^2 = 1.5\pm0.2$, E_{GTR} =18.19 MeV, E_{IAR} = 21.16 MeV (I^π=3/2$^-$, T = 5/2).

Decay to ^{11}Be, E_{level} in MeV [10, 26]	lg ft [10, 26]	B(GT) in $(g_V)^2/4\pi$, (5) was used
0.32	5.67±0.04	0.013
2.69	5.06±0.10	0.053
3.41	6.25±0.10	0.0035
3.890±0.001	4.78±0.10	0.102
3.97±0.02	5.3±0.2	0.0308
5.24	5.55±0.08	0.017
7.03	5.77±0.09	0.01
8.02±0.02	4.30±0.08	0.308
8.82	4.46±0.07	0.213
10.06	4.18±0.12	0.406
16.3	4.66±0.08	0.138
18.19	2.45±0.13	21.81
Ikeda sum rule $\Sigma=15(g_A^{eff})^2/4\pi$		$\Sigma=23(g_V)^2/4\pi$

Because GT strength B(GT) for resonance at 18.19 MeV energy (B(GT)=$21.8(g_V)^2/4\pi$, Table 1) has a large value, we conclude that this resonance (E_{GTR}=18.19 MeV) in ^{11}Be corresponds to the GTR. For ^{11}Be we have [10,18,25] E_{IAR} = 21.16 MeV, i.e. $E_{GTR} < E_{IAR}$.
Resonances of GT type were not observed in ^{11}Be at the excitation energies more than Q_β. The total strength of all observed beta transitions of ^{11}Li is very strong from the point of view of Ikeda sum rule. For $|$N-Z$|$ » 0 nuclei theory predict the maximum excitation energy for the main resonance (GT resonance) [1,2] in S_β(E). If some additional resonance of GT type will exist at excitation energy higher than 18.19 MeV, it will have, because $|$N-Z$|$ » 0, comparable strength with the 18.19 MeV resonance. In such situation we will have additional large GT strength and very strong modification of g_A^{eff} in contradiction with [11] systematic. We neglected by possible contribution of the experimentally unobserved GT strength at the energy higher than 18.19 MeV in ^{11}Be to the Ikeda sum rule.

Compare the experimental value (Table 1 and Fig. 3) of total sum of B(GT) with the Ikeda sum rule (8), (9) we obtained that $(g_A^{eff}/g_V)^2 = 1.5\pm 0.2$ for ^{11}Li.

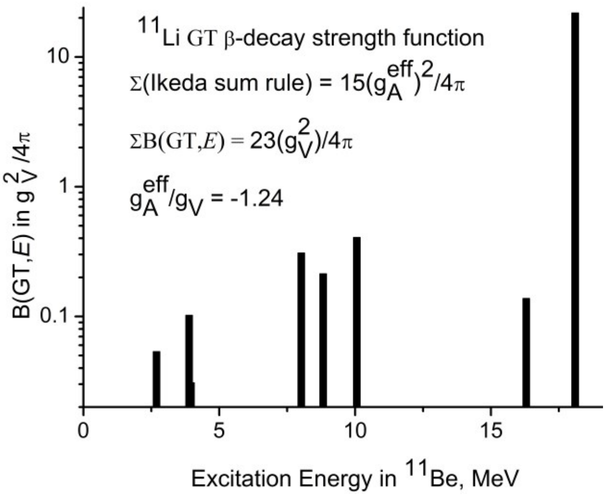

Fig. 3. Structure of the β-decay strength function for ^{11}Li GT β^--decay in $g_V^2/4\pi$ units.

5 Evolution of E_{GTR}-E_{IAS} toward 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 $E_{IAR} \approx E_{GTR}$. 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 [1,12,24,26].

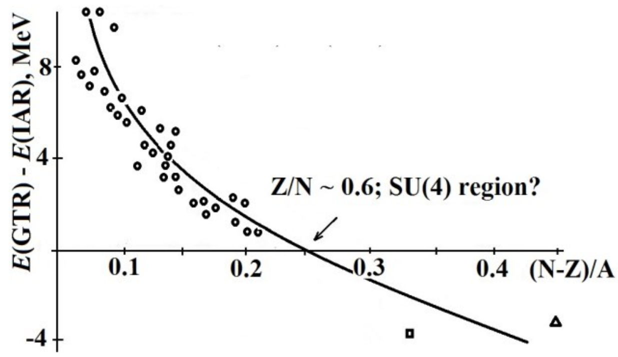

Fig. 4 The difference of the E_{GTR} - E_{IAR} energies (circles) as a function of the neutron excess [1,12]. Data for ^{6}He (square) [7] and for ^{11}Li (triangle) β^--decays were added.

This fact may be interpreted as an approximate SU(4) symmetry realization in a definite nuclear area, namely for nuclei with grate $(N\text{-}Z)/A$, where spin-isospin SU(4) symmetry determine the nuclear properties (SU(4) region). From simple estimation (Fig.4) follows that the value $Z/N \approx 0.6$ corresponds to the SU(4) region. The interesting feature shown in Fig.4 is that the GTR energy is lower than the IAR energy for very neutron-rich nuclei. There is more complicated dependence of E_{GTR} - E_{IAR} on $(N\text{-}Z)/A$ than linear for the nuclei fare from β-stability line. Shell-model [27] also predict 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. It is thus interesting to measure more detail the evolution of E_{GTR} - E_{IAR} for neutron-rich nuclei fare from β-stability line.

6 Summary

The quenching of g_A can be observed in GT β^--decay of halo nuclei, where $E_{\mathrm{GTR}} < E_{\mathrm{IAR}}$ [7] and GTR (or low-energy super Gamow-Teller phonon [8,9]) may be observed. Method of g_A^{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. Compare experimental total strength for β-decay in $g_V^2/4\pi$ units with the Ikeda sum rule (in $(g_A^{eff})^2/4\pi$ units), we obtained $(g_A^{eff}/g_V)^2 = 1.272 \pm 0.010$ for ^{6}He GT β^--decay and $(g_A^{eff}/g_V)^2 = 1.5 \pm 0.2$ for ^{11}Li GT β^--decay.

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

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