

6-22-2019

## Structure of $\beta$ -decay strength function $S\beta(E)$ and Wigner spin-isospin SU(4) symmetry

I. N. Izosimov

*Joint Institute for Nuclear Research ,Russian Federation ,*

Follow this and additional works at: <https://www.ephys.kz/journal>



Part of the [Materials Science and Engineering Commons](#), and the [Physics Commons](#)

### Recommended Citation

Izosimov, I. N. (2019) "Structure of  $\beta$ -decay strength function  $S\beta(E)$  and Wigner spin-isospin SU(4) symmetry," *Eurasian Journal of Physics and Functional Materials*: Vol. 3: No. 2, Article 5.  
DOI: <https://doi.org/10.29317/ejpfm.2019030205>

This Original Study is brought to you for free and open access by Eurasian Journal of Physics and Functional Materials. It has been accepted for inclusion in Eurasian Journal of Physics and Functional Materials by an authorized editor of Eurasian Journal of Physics and Functional Materials.

# Structure of $\beta$ -decay strength function $S_{\beta}(E)$ and Wigner spin-isospin SU(4) symmetry

I. N. Izosimov

Joint Institute for Nuclear Research, Dubna, Russia

E-mail: izosimov@jinr.ru

DOI: 10.29317/ejpfm.2019030205

Received: 20.05.2019 - after revision

It is shown that when the parent nucleus has  $nm$  Borromean halo structure, then after Gamow-Teller (GT)  $\beta$ -decay of parent state or after M1  $\gamma$ -decay of Isobar Analogue Resonance ( $IAR$ ) the states with  $np$  tango halo structure or mixed  $np$  tango +  $nm$  Borromean halo structure can be populated. Resonances in the GT  $\beta$ -decay strength function  $S_{\beta}(E)$  of halo nuclei may have  $np$  tango halo structure or mixed  $np$  tango +  $nm$  Borromean halo structure. Demonstrated that the nuclei with  $Z/N \approx 0.6$  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 ( $\pi p$ )-neutron hole ( $\nu h$ ) coupled into a spin-parity  $I^{\pi} : [\pi p \otimes \nu h]I^{\pi}$  and neutron particle ( $\nu p$ )-proton hole ( $\pi h$ ) coupled into a spin-parity  $I^{\pi} : [\nu p \otimes \pi h]I^{\pi}$ . The strength function of Fermi-type  $\beta$ -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  $\beta$ -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  $M1 \gamma$ -decay of  $IAR$  with  $np$  Borromean halo structure or  $GT \beta$ -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  $GT \beta$ -transitions essential configurations include states made up of the ground state of parent nucleus by the action of the Gamow-Teller operator of the  $\beta$ -transition [1, 2]  $Y_-$  :

$$Y_- = \sum \tau(i) - \sigma(i), \quad (1)$$

where  $\tau(i) - \sigma(i)$  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 ( $\pi p$ )-neutron hole ( $\nu h$ ) 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 corresponding 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).

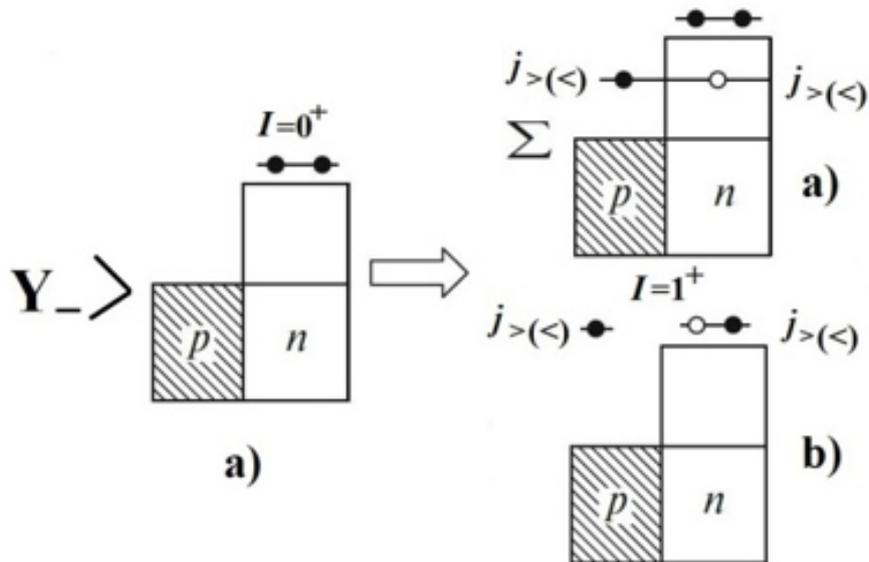


Figure 1. Proton particle–neutron hole coupled to form the spin-parity  $I = 1^+$  and core polarization (CP) states, where  $j_> = 1+1/2$ ,  $j_< = 1-1/2$ , a)  $nn$  Borromean halo component, b)  $np$  tango halo component.

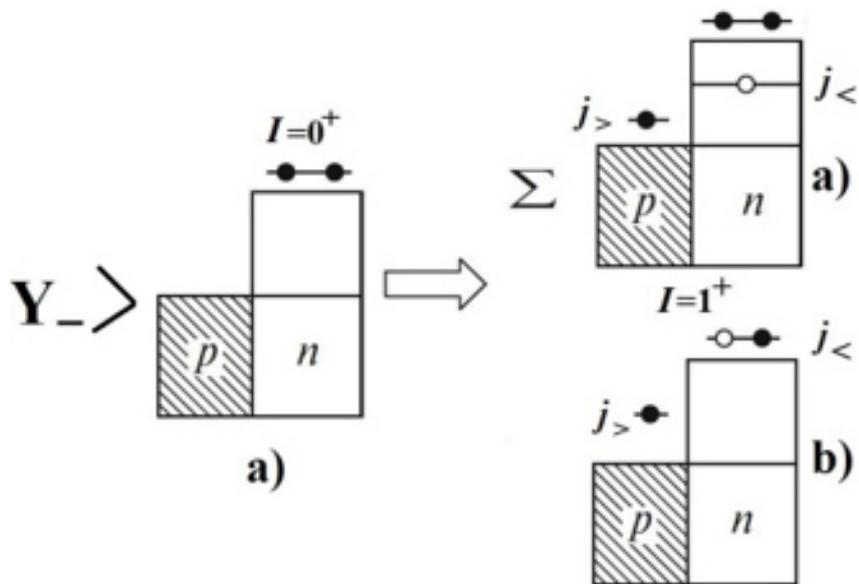


Figure 2. Proton particle–neutron hole coupled to form the spin-parity  $I = 1^+$  and back spin flip (BSF) states: a)  $nn$  Borromean halo component, b)  $np$  tango halo component.

## Gamow-Teller $\beta$ -decay of ${}^6\text{He}$ , M1 $\gamma$ -decay of $IAR$ in ${}^6\text{Li}$ and $SU(4)$ region

Two neutrons that form the  $nn$  halo in  ${}^6\text{He}$  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  ${}^6\text{He}$  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  ${}^6\text{Li}$  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

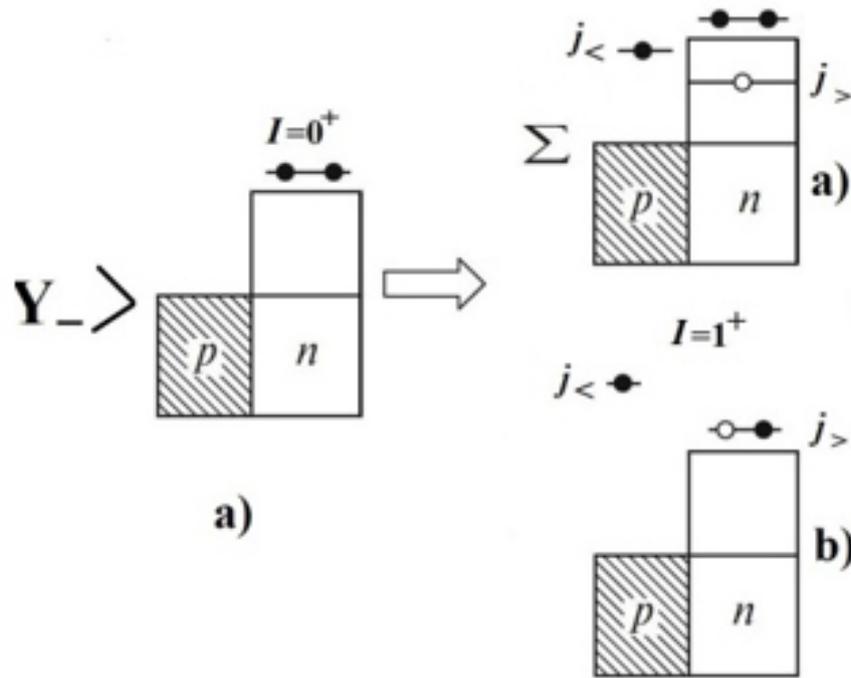


Figure 3. Proton particle–neutron hole coupled to form the spin-parity  $I = 1^+$  and spin flip (SF) states: a)  $nn$  Borromean halo component, b)  $np$  tango halo component.

$T_{1/2} = 6 \cdot 10^{-17}$  s. The theoretical and experimental data [10-12] indicate that this  $IAR$  state has a  $np$  halo. Since the operators of GT  $\beta$ -decay and  $M1$   $\gamma$ -decay have no spatial components (the radial factor in the  $M\lambda$   $\gamma$ -transition operator is proportional to  $r^{\lambda-1}$ ), GT  $\beta$ -transitions and  $M1$   $\gamma$ -transitions between states with similar spatial shapes are favored. The  $M1$   $\gamma$ -decay of IAS would be hindered [9] if the g.s. of  ${}^6\text{Li}$  did not have a halo structure and would be enhanced if the g.s. of  ${}^6\text{Li}$  has a halo structure. A rather large value of the reduced probability of  $M1$   $\gamma$ -transition ( $B(M1, \sigma) = 8.2$  W.u.) for  $M1$   $\gamma$ -decay from IAS and large  $B(\text{GT}) \approx 5g_A^2/4\pi$  ( $\Sigma$  Ikeda sum rule)  $= 6g_A^2/4\pi$  value for  $\beta$ -transition to the ground state is evidence [9] for the existence of tango halo structure in the  ${}^6\text{Li}$  ground state. Because of large  $B(\text{GT})$  value ( $B(\text{GT}) \approx 5g_A^2/4\pi$ ), the  ${}^6\text{Li}$  g.s. has structure corresponding to the low-energy Gamow-Teller phonon [13, 14] and the energy of this GT phonon is lower than ( $E_{\text{GT}} < E_{\text{IAR}}$ ) the energy of  $IAR$  ( $E_{\text{IAR}} = 3562.88$  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  $IAR$  ( $E_{\text{GT}} > E_{\text{IAR}}$ ). 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 excited in the final nucleus [1, 15]. This model was originally used to analyze  $M1$   $\gamma$ -decay of  $IAR$ , the  $\beta$ -decay strength functions from the spectra of delayed neutrons, and the probabilities of  $\beta$ -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.

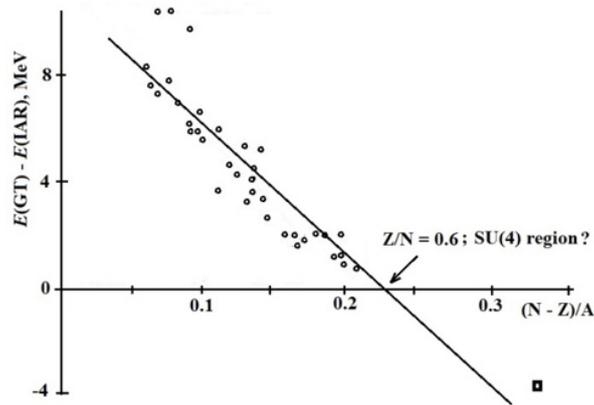


Figure 4. Difference of the  $E_{GT} - E_{IAR}$  energies (circles) as a function of the neutron excess [15]. Datum for  ${}^6\text{He}$   $\beta$ -decay was added (square).

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  ${}^6\text{Li}$  (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  ${}^6\text{He}$  ( ${}^6\text{He}$  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  $S_\beta(E)$  for halo nuclei may have structure corresponding to np tango halo. When neutron excess is high enough, resonances in  $S_\beta(E)$  may simultaneously have both *nn* Borromean halo component and np tango halo component and form so-called mixed halo. Structure of resonances in  $S_\beta(E)$  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.

## References

- [1] Yu.V. Naumov et al., Sov. J. Part. Nucl. **14** (1983) 175.
- [2] I.N. Izosimov et al., Phys. of Part. and Nucl. **42** (2011) 963.
- [3] I. Tanihata, J. Phys. G: Nucl. Part. Phys. **22** (1996) 157.
- [4] A.S. Jensen et al., Rev. Mod. Phys. **76** (2004) 215.

- [5] B. Jonson, Phys. Rep. **389** (2004) 1.
- [6] I.N. Izosimov Vladivostok, Russia (2012) (World Scientific, 2013) 129-133.
- [7] I.N. Izosimov, AIP Conference Proceedings **1681** (2015) 030006.
- [8] I.N. Izosimov et al., EPJ Web of Conf. **107** (2016) 09003.
- [9] I.N. Izosimov, Phys. of At. Nucl. **88** (2017) 867.
- [10] Y. Suzuki and K. Yabana, Phys. Lett. B **272** (1991) 173.
- [11] L. Zhihong et al., Phys. Lett. B **527** (2002) 50.
- [12] <http://www.nndc.bnl.gov>.
- [13] Y. Fujita et al., Phys. Rev. Lett. **112** (2014) 112502.
- [14] Y. Fujita et al., Phys. Rev. C **91** (2015) 064316.
- [15] I.N. Izosimov, Phys. of Part. and Nucl. **30** (1999) 131.
- [16] E.P. Wigner, Phys. Rev. **51** (1937) 106.
- [17] Yu.S. Lutostansky et al., Phys. of At. Nucl. **79** (2016) 929.
- [18] M. Chakraborty et al., Phys. Rev. Lett. **45** (1980) 1073.
- [19] Yu.V. Gaponov et al., Heavy Ion Physics **3** (1996) 189.