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Borromean halo, Tango halo, and halo isomers in atomic nuclei

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Abstract. Structure of the ground and excited states in halo-like nuclei is discussed. Both the Borromean and tango halo types can be observed for *n-p* configurations of atomic nuclei.Structure of the halo may be different for the different levels and resonances in atomic nuclei. Isobar analog, double isobar analog, configuration, and double configuration states can simultaneously have *n-n, n-p,* and *p-p* halo components in their wave functions. When the halo structure of the excited state differs from that of the ground state, or the ground state has non-halo structure, the γ-transition from the excited state to the ground state can be essentially hindered, i.e. the formation of a specific type of isomers (halo isomers) becomes possible. $B(M\lambda)$ and $B(E\lambda)$ values for γ-transitions in ^{6,7,8}Li, ^{8,9,10}Be, ^{8,10,11}B, ^{10,11,12,13,14}C, ^{13,14,15,16,17}N, ^{15,16,17,19}O, and ^{17}F are analyzed. Special attention is given to nuclei which ground state does not exhibit halo structure but the excited state (halo isomer) may have one.

1 Introduction

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 [1-3]. 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 [1-3]. 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 [2]. Halo of Borromean type is well known in atomic nuclei [4]. Halo of tango type is well known in molecules [2]. Characteristics of the γ-transitions in ^{6}Li are analyzed. It is shown that the ground state (g.s.) of atomic nucleus ^{6}Li ($J=1^+$, S_n=5.66 MeV, S_p=4.59 MeV, S_d=1.47 MeV) may be a good candidate for halo state of tango type.

The Isobar Analog State (IAS) of the ^{6}He g.s. (two-neutron halo nucleus), i.e., the 3.56 MeV, $J=0^+$ state of ^{6}Li, has [5,6] a neutron-proton halo structure of Borromean type. For N>Z nuclei the IAS [7] is the coherent superposition of the excitations like neutron hole–proton particle coupled to form the momentum $J^\pi=0^+$. The IAS has the isospin $T=T_z+1=(N-Z)/2+1$, where $T_z=(N-Z)/2$ is the isospin projection. The isospin of the g. s. is $T=T_z=(N-Z)/2$. When the IAS energy corresponds to the continuum, the IAS can be observed as a resonance. Configuration states (CS) are not the coherent superposition of such excitations and have $T=T_z=(N-Z)/2$. One of the best studied CS is the anti-analog state (AIAS) [7,8]. The CS formation may be restricted by the Pauli principle. The Double Isobar Analog State (DIAS) has the isospin $T=T_z+2$ and is formed as the coherent superposition of the excitations like two neutron holes–two proton particles coupled to form the momentum $J = 0^+$. The corresponding configurations for nuclei with Z>N are formed under substitution of proton with neutron, which has similar spin and spatial state characteristics. Thus in Z>N nuclei, proton-particle and neutron-hole elementary excitations coupled to form the momentum $J=0^+$ are replaced by elementary excitations, like neutron-particle and proton-hole coupled to form the momentum $J=0^+$.

Strong mixing with other more complicated states dilutes the component of the halo. High level density of non-halo levels prevents halo formation [2] in the excited states. There may be only a small window open for halo occurrence. How small this window is, it can be answered by study halo in excited states. Isospin symmetry essentially reduces mixing of the configurations with different isospin quantum number and is favorable for halo formation. Such excited states and resonances as IAS, DIAS, CS, and DCS in nuclei may simultaneously have *n-n, n-p,* and *p-p* halo components in their wave functions [8]. Excited halo states and resonances of non-IAS structure may also occur in atomic nuclei [2,3,9,10]. Differences in halo structure of the excited and ground states can result in the formation of isomers (halo-isomers). From this point of view some CS and DCS depending on theirs halo structure, may be observed as halo isomers.Structure of

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the ground and excited states in halo like nuclei is discussed. Values of reduced probability B*(Mλ)* and B*(Eλ)* for γ-transitions in ^{6,7,8}Li, ^{8,9,10}Be, ^{8,10,11}B, ^{10,11,12,13,14}C, ^{13,14,15,16,17}N, ^{15,16,17,19}O, and ^{17}F are analyzed. Special attention is given to the nuclei where the ground state (g. s.) has no a halo structure but some excited states (halo isomers) may be of a halo structure.

2 Borromean *n-p* halo for IAS, tango *n-p* halo for g. s. in ^{6}Li

Two neurons that form the *n-n* halo in ^{6}He g. s. (T=1, T_z=1) 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 IAS structure corresponding to the *p-n* halo and formation of CS is prohibited by the Pauli principle. 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 Γ=8.2 eV, which corresponds to the half-life $T_{1/2}$=6·10^{-17} s. The experimental data [5,6] indicate that this state has a *n-p* halo. The γ-decay of IAS would be hindered if the g. s. of ^{6}Li did not have a halo structure. The data on lifetime of IAS in ^{6}Li are given in [11], but the *M*1 γ-decay branch is not determined. If one assumes that the total lifetime of IAS is determined by *M*1 γ-decay, the reduced transition probability would be B(*M*1)=8.6 W.u. Assuming the orbital part of the *M*1 γ-transition operator is neglected [7], B(*M*1,σ) for *M*1 γ-decay of IAS in ^{6}Li can be determined from the reduced probability *ft* of the ^{6}He β-decay (Fig.1). The B(*M*1,σ) value proved to be 8.2 W.u., i.e. the probability of the *M*1 γ-transition is close to the value for the upper limit in the light nuclei region [11].

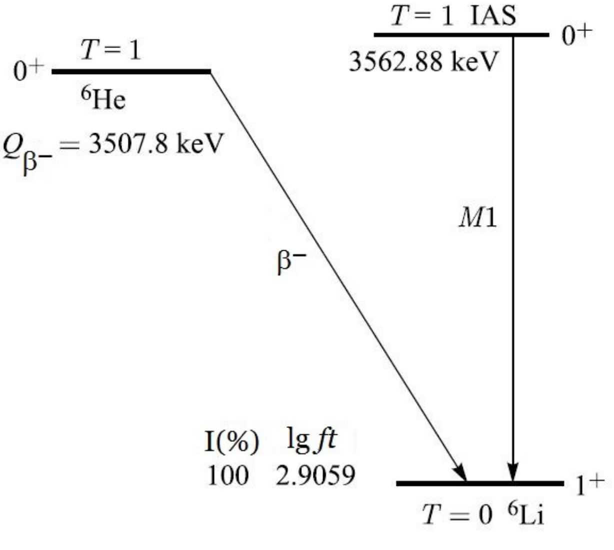

Figure 1. Connection [7] between the *ft* value for *β*-decay of the parent state (^{6}He g.s.) and the B(*M*1,σ) value for γ-decay of the IAS (^{6}Li, E=3562 keV). $ft = 11633/[T_0 \times B(M1,\sigma)]$, T_0-isospin of the parent state, *ft* in sec, B(M1,σ) in μ_0^2 , for M1 γ-transition W.u.=1.79 μ_0^2 , B(M1,σ) = 8.2 W.u., B(*M*1) ≈ 8.6 W.u.

Considerable overlap of wave functions of the two halo states (i.e. the IAS halo state and halo g. s.) in ^{6}Li results in significant increase of the probability of *M*1 γ-transition between the states. In the absence of halo structure in the g. s. of ^{6}Li, a corresponding *M*1 γ-transition would be hindered. A rather large value of the reduced probability (B(*M*1,σ)=8.2W.u.) of *M*1 γ-transition for *M*1 γ-decay from IAS to the g. s. is evidence for the existence of tango halo structure in the ^{6}Li g. s. The IAS in ^{6}Li has the Borromean structure since the *n-p* subsystem is coupled to the momentum $J = 0^+$, i.e. unbound, whereas *n-p* subsystem for the ^{6}Li g. s. is coupled to the momentum $J = 1^+$, i.e. bound. According to halo classification [2], such structure of the ^{6}Li g. s. corresponds to the tango halo. Such conclusion agrees with the data on the properties of ^{6}Li nucleus and on the properties of nuclear reactions with ^{6}Li beams. The radius of the ^{6}Li nucleus ranges between 2.32 fm and 2.45 fm, and this is 10% larger than the radius value expected from the available systematics. The ^{6}Li nucleus is known to have the ($\alpha + d$) cluster structure (the energy threshold for the breakup of this nucleus into a deuteron and an alpha particle is as low as 1.47 MeV) [11]. The momentum distributions of ^{4}He from the ^{6}He and ^{6}Li breakup were measured for different targets and beam energies. The observed momentum distributions are narrow for the ^{6}He breakup (σ=28−29MeV/c) and intermediate for the ^{6}Li breakup (σ=46−55MeV/c) [12,13]. For ordinary (non-halo) nuclei, this value would have been about σ~100MeV/c. The small width of the momentum distribution confirms the presence of halo in ^{6}He [12,13]. Intermediate width of the momentum distribution supports hypothesis of *n-p* halo of tango type in ^{6}Li g.s.

3 Systematic of the B(*M*,λ) and B(*E*,λ) values for γ-transitions in ^{6,7,8}Li, ^{8,9,10}Be, ^{8,10,11}B, ^{10,11,12,13,14}C, ^{13,14,15,16,17}N, ^{15,16,17,19}O, and ^{17}F. Halo isomers

Isovector (IV) and isoscalar (IS) parts [7] may be separated in the γ-transition operator. For IV/IS γ-transition only IV/IS part gives contribution to the probability of γ-decay. Selection rules on isospin for γ-transitions are: ΔT = 0, ±1; ΔTz=0. For ΔT = ±1 - only IV part gives contribution to the matrix element (IV-transitions). For ΔT = 0 (T ≠0) - both IV and IS parts of γ-transition operator give contribution (mixing of IV and IS). For N=Z (Tz=0) IV component does not give contribution to the transitions between T=0 states (IS-transitions). For *E*1 γ-decay only IV part gives contribution to the matrix element and *E*1 γ-transitions between T=0 states are forbidden on isospin in N=Z nuclei. In the 20 ≤ A ≤40 nuclei [7,14] contribution of the IS part for γ-transitions is about: for *M*1 γ-transitions – 0.01; for *M*2 γ-transitions – 0.01; for *M*L, L>2 γ-transitions – 0.2; for *E*1 γ-transitions about 0.03 (T-forbidden transitions, isospin mixture about 3%). For *E*L γ-transitions with L≥2 it is difficult to make some conclusion about contribution of the IS part. On isospin quantum number the γ-transitions may be classify [7] as favorable (ΔT = 1; Tz=0), usual (ΔT = 0, ±1; Tz≠0), hindered (ΔT = 0; Tz=0).

Data on B(M,λ) and B(E,λ) from [11] were used for analysis of γ-transitions. The distributions of the lg(B(M,λ)) and lg(B(E,λ)) values for γ-transitions in ^{6,7,8}Li, ^{8,9,10}Be, ^{8,10,11}B, ^{10,11,12,13,14}C, ^{13,14,15,16,17}N, ^{15,16,17,19}O, and ^{17}F nuclei were the objects of our analysis. The mean values < B(M,λ)> and < B(E,λ)> are in agreement with previous systematics [7,14], but one can indicate the tails (Fig.2) for in lower lg(B(M,λ)) and lg(B(E,λ)) value parts of distributions. These tails may be connected with halo isomers.

When the halo structure of the excited state differs from that of the g. s., or the g. s. has non-halo structure, the γ-transition from the excited state to the g.s. can be essentially hindered, i.e. the formation of a specific type of isomers (halo isomers) becomes possible. The particularity of halo isomer observations lies in the fact that it is necessary to analyze partial γ-decay lifetime. The radial factor r^{λ} for the electric and $r^{\lambda-1}$ for the magnetic multipole γ-transition operator of order λ may compensate the differences in the large-distance parts of halo and non-halo wave functions. Here r is the core-halo distance. The most sensitive for detection of the γ-transition hindrance between halo→ non-halo states will be M1 γ-transitions (or may be E1 and M2).

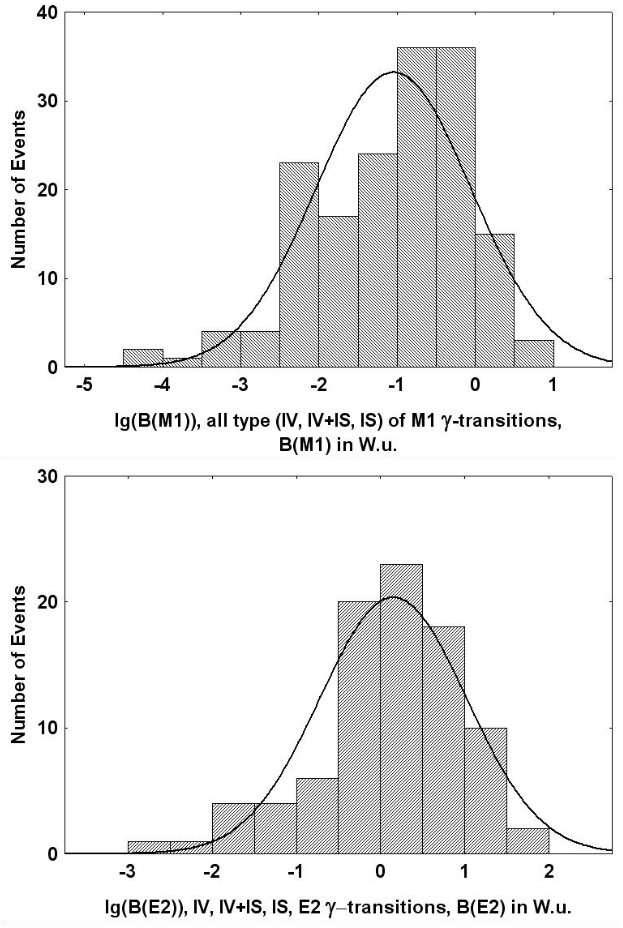

Figure 2. Distributions of the lg(B(M1)) (a) and lg(B(E2)) (b)values for γ-transitions in ^{6,7,8}Li, ^{8,9,10}Be, ^{8,10,11}B, ^{10,11,12,13,14}C, ^{13,14,15,16,17}N, ^{15,16,17,19}O, and ^{17}F. Mean values: <lg(B(M1))> = -1.0; <B(M1)>=0.1W.u.; standard deviation σ(lg(B(M1)))=0.99; <lg(B(E2))> = 0.15; <B(E2)>=1.4W.u.; σ(lg(B(E2)))=0.87.

Table 1. Halo (intermediate halo) → halo (intermediate halo) γ-transitions. [$T_{1/2}$(s)×Γ(eV)] = 4.8 · 10^{-16}.

Nuclei/γ-transition
^{6}Li, IAS, E_{lev}=3.56MeV, $I^{\pi}=0^{+}$, T=1 $\rightarrow$ ^{6}Li, g.s., $I^{\pi}=1^{+}$, T=0, S_n=5665 keV, S_p=4593keV, S_d=1474keV. B(M1) =8.6 W.u., $T_{1/2}$ = 5.9 · 10^{-17} s.
^{9}Be, S_n=1665.4keV, S_p=16888.2keV; E_{lev}=1.68MeV, $I^{\pi}=½^{+}$ $\rightarrow$ g.s., $I^{\pi}=3/2^{-}$, B(E1)=0.22W.u., $\Gamma\gamma$=0.30eV.
^{8}B, S_n=13MeV, S_p=137.5keV; E_{lev}=0.7695MeV, $I^{\pi}=1^{+}$, $\Gamma\gamma$=0.0252eV $\rightarrow$ g.s. $I^{\pi}=2^{+}$, B(M1)=2.63 W.u.
^{10}C, S_n=21283.1 keV, S_p=4006.0 keV, S_{2p}= 3820.9 keV;E_{lev}=3.353 MeV, $I^{\pi}=2^{+}$, $\rightarrow$ g.s. $I^{\pi}=0^{+}$, B(E2)=9.6 W.u. $T_{1/2}$ = 155 fs (4.25 · 10^{-3} eV).
^{10}Be, S_n=6812keV, S_p=19.636MeV; E_{lev}=7371keV, $I^{\pi}=3^{-}$ $\rightarrow$ E_{lev}=5958 keV, $I^{\pi}=2^{+}$, B(E1)=0.12 W.u., $\Gamma\gamma$ = 0.11eV.
^{11}Be, S_n=501.62keV, S_p=20.1MeV; E_{lev}=320keV,$I^{\pi}=½^{-}$ $\rightarrow$ g.s., $I^{\pi}=½^{+}$, B(E1)=0.36W.u., $T_{1/2}$=115 fs.
^{10}B, S_n=8436.3 keV, S_p=6585.9 keV; E_{lev}=6875KeV, $I^{\pi}=1^{-}$, T=0+1(mixture) $\rightarrow$ E_{lev} =5919 keV, $I^{\pi}=2^{+}$, T=0, B(E1) = 0,19 W.u. (due to isospin mixture), $\Gamma\gamma$ = 0.054eV.
^{17}F, S_n=16800keV, S_p=600.27keV; E_{lev}=495keV, $I^{\pi}=½^{+}$$\rightarrow$ g.s. $I^{\pi}=5/2^{+}$, B(E2)=25W.u. $T_{1/2}$ = 286 ps

Table 2. Halo (intermediate halo) → non-halo γ-transitions.

Nuclei/γ-transition
^{10}B, S_n=8436.3 keV, S_p=6585.9 keV; E_{lev}=5919 keV, $I^{\pi}=2^{+}$ $\rightarrow$ g.s., $I^{\pi}=3^{+}$, B(M1)=0.026 W.u. $\Gamma\gamma$=0.112eV; $\rightarrow$ E_{lev}=718 keV, $I^{\pi}=1^{+}$, B(M1)=0.0085 W.u., $\Gamma\gamma$=0.025eV.
^{10}Be, S_n=6812 keV, S_p=19636 keV; E_{lev}=5958.39 keV, $I^{\pi}=2^{+}$, $T_{1/2} \leq$ 55fs (>90%) $\rightarrow$ E_{lev}=3368 keV, $I^{\pi}=2^{+}$, B(M1)≈0.03 W.u.
^{14}N, S_n=10553.3 keV, S_p=7550.6 keV; E_{lev}=6.20 MeV, $I^{\pi}=1^{+}$$\rightarrow$ g.s., $I^{\pi}=1^{+}$, B(E2)=0.021 W.u., B(M1)=0.0018 W.u., $T_{1/2}$=160 fs
^{14}N, S_n=10553.3 keV, S_p=7550.6 keV; E_{lev}=9.13 MeV, $I^{\pi}=3^{+}$,$T_{1/2}(\gamma)$=45 fs $\rightarrow$ g.s., $I^{\pi}=1^{+}$, B(E2)=0.0081 W.u; $\rightarrow$ E_{lev}=5.83 MeV, $I^{\pi}=3^{-}$, B(E1)=6.4 · 10^{-5} W.u; $\rightarrow$ E_{lev}=6.45 MeV, $I^{\pi}=3^{+}$, B(M1)=2.2 · 10^{-3} W.u.
^{14}N, S_n=10553.3 keV, S_p=7550.6 keV; E_{lev}=9.70 MeV, $I^{\pi}=1^{+}$, $\Gamma\gamma$ = 0.06 eV $\rightarrow$ g.s., $I^{\pi}=1^{+}$, B(M1)=0.00094 W.u; $\rightarrow$ E_{lev}=2.31 MeV, $I^{\pi}=0^{+}$, T=1, B(M1)=5.1 · 10^{-3} W.u

Using an available body of evidence [11] on γ-decay for 6 $\leq$A $\leq$17 nuclei, we selected halo (intermediate halo) →halo (intermediate halo) γ-transitions. B($M\lambda$) and B($E\lambda$) (Table 1) for such types of γ-transitions are fairly large near the upper limit [11] within selected nuclear region. This implies high overlapping (especially for M1 γ-transitions) of wave functions of the initial and final states of nuclei undergoing γ-transition.

As a next step, we selected excited states of nuclei whose characteristics were suitable for halo formation (low binding energy and angular momentum), γ-decay was hindered, multipolarity of transitions was small, and the final state of γ-decay had *a fortiori* a non-halo structure (large binding energy). The data on γ-decay of halo (intermediate halo) ⟶ non-halo type are presented in Table 2. The comparison of data from Tables 1 and 2 shows that the reduced probabilities of halo → non-halo γ-transitions (Table 2) are far lower than those of halo → halo γ-transitions (Table 1). The hindrance factor can reach 10^4 for *M*1 γ-transitions, $5{\cdot}10^4$ for E1 γ-transitions, and 10^2 for *E*2 γ-transitions.

4 Conclusions

1. IAS, DIAS, CS, and DCS can simultaneously have *n-n, n-p,* and *p-p* halo components in their wave functions.
2. A large value of the reduced probability of *M*1 γ-transition from IAS to the ground state is evidence for the existence of tango halo structure in the ^{6}Li ground state ($J=1^+$, S_n=5.66 MeV, S_p=4.59 MeV, S_d=1.47 MeV).
3. For A=6-19 nuclei the hindrance factor of *M*1 γ-transitions is up to 10^4 for halo → non-halo in comparison with halo → halo γ-transitions, up to $5{\cdot}10^4$ for *E*1 γ-transitions, up to 10^2 for *E*2 γ-transitions.
4. Differences in halo structure of the excited and ground states can result in the formation of isomers (halo isomers).

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